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(54) **Remote measurement of physical variables with fiber optic systems.**

(57) The invention relates to methods and devices for measuring physical parameters by converting a fraction of the intensity of the interrogating light into a positive optical signal with wavelengths and/or light propagation modes different from those of the interrogating light, and having at least one characteristic which is a known function of the physical parameter being measured. The invention is adapted to the measurement of distributed forces and/or temperatures along a continuous length of optical fiber, and to the non-invasive coupling of information into an optical fiber from the side at any point or a multiplicity of points. The optical fiber is so designed that information signals coupled into it simultaneously at different points are separable at one end of the fiber and measurable without interference from each other.

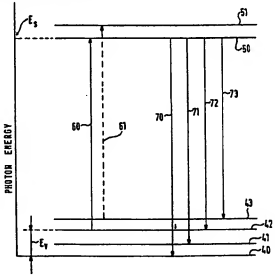

Fig. 1

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REMOTE MEASUREMENT OF PHYSICAL VARIABLES WITH FIBER OPTIC SYSTEMS

Cross-Reference to Related Applications

This is a continuation-in-part of copending application Ser. No. 102,835 filed Sep. 30, 1987, which in turn is a continuation-in-part of application Ser. No. 711,062 filed March 12, 1985, which in turn is a continuation-in-part of application Ser. No. 608,932 filed May 14, 1984, now U.S. Pat. No. 4,708,494 which in turn is a continuation-in-part of application Ser. No. 405,732 filed August 6, 1982, now abandoned.

Background of the Invention

The present invention relates to improved methods and devices for the remote measurement of physical variables with fiber optic systems, and more particularly is directed to the novel use of luminescence and Raman scattering techniques for increasing the measuring capability of sensing systems and the accuracy of the measuremnts made with them.

Description of the Prior Art.

Fiber optic sensing systems have been under development in recent years for the remote measurement of physical variables (also referred to as measurands) of interest in industry, medicine, transportation, and other fields of human endeavor. There are two main approaches to fiber optic sensing, as follows:

(a) The use of the optical fiber itself as the transducer, in a system which may be interferometric or non-interferometric, and

(b) The use of a point transducer attached or otherwise optically connected to one or more optical fibers, the latter acting merely as light guides.

These and other approaches are discussed in a recent review by G.D. Pitt et. al., IEE Proceedings, Vol 132, Pt. J. No. 4, August 1985, pp214-248.

In addition, optical fibers are used for transmitting the information of sensors, whether optical or electrical, to a remote control station.

Interferometric sensing systems use the fibers themselves as transducers, and can achieve high sensitivities. They have, however, several disadvantages. They usually require single mode lasers, single mode fibers, and relatively complex instruments, and are often subject to drift and phase noise due to environmental factors other than the parameter sought to be measured. Further, they are not presently compatible with the industrial requirements for ruggedness. Non-interferometric systems, which usually use multimode fibers and non-coherent light sources, are simpler, more rugged, and are capable of meeting most of the sensitivity requirements of industry. The methods and devices of this invention are based on non-interferometric systems.

Many fiber optic sensing systems are based on light intensity changes produced by the action of the measured. In order to obtain a reliable measurement of the physical variable with such systems, it is necessary to compare the optical signal generated by the measured to a reference signal which is not affected by this measurand. This is done in the prior art by any of the following ways:

(a) If the sensor is not spectrally selective, by splitting the light output from the interrogating light source into two separate beams each carried by a separate fiber. One of the beams is made to interact with the measurand, where its intensity is modulated according to the measurand's value. The other beam is used as a reference. The modulated beam and the reference beam are sent through separate optical paths to separate photodetectors, and the resulting electrical signals are compared. The value of the measurand is determined from the relative values of the two electrical signals.

(b) If the sensor is spectrally selective, by interrogating the probe with light of an intensity distributed in a known manner between two wavelength regions, the intensities of each of these spectral components modulated in a known, different manner by the probe. There are two ways to accomplish this. One way is to carry both spectral components simultaneously by the same fiber, and then to separate them at the fiber output (after interaction with the sensor) by means of wavelength-selective optical filters, feeding each

separate beam to a separate photodetector. The other way is to use a switching device to send both spectral components alternately through the same fiber system to the same photodetector. The latter method was used to measure temperature by monitoring the temperature-dependent light transmission of semiconductor crystals within their absorption band edge (Kyuma et. al., IEEE J. Quant. Electron., QE-18(4), 677 (1982)).

Each of the above methods is subject to error, due to unequal detector drift, varying losses in the separate optical paths and/or unequal fluctuations in the intensities of the spectral components of the interrogating light source(s).

In the prior art sensors described above, so-called intensity sensors, the value of the measurand is determined indirectly from the attenuation of the intensity P_o of the interrogating light incident on the sensor to a transmitted value $P_o(1-\alpha)$. The value of α, which is an indicator of the value of the measurand, is estimated indirectly from the measurement of the transmitted light intensity. It is well known that such measurements can not be made with a high degree of accuracy when the optical density is of the order of 10^{-3} or lower for a single, discrete sensor. The accuracy of said attenuation measurements is further degraded in the case of series-multiplexed sensors, where the attenuation measurements must be carried out by optical time domain reflectometry (OTDR) techniques, which consist of the measurement of the decrease of the intensity of the Rayleigh-backscattered light caused by each sensor. In this case a measurement with an accuracy of one percent may require the accurate and reproducible measurement of light intensity changes of a few parts per 10^4. This is difficult to achieve with a relatively simple device, especially considering that Rayleigh-backscattered light signals are reletively weak, with an intensity down about 45 to 50 dB with respect to the intensity of the interrogating light at the same fiber location.

Most non-interferometric fiber optic sensing systems operate by measuring the measurand-dependent variable light transmission of the sensor, and their performance is subject to the inherent limitations discussed in the preceding paragraph. Temperature-sensing systems include, besides the one already mentioned by Kyuma et. al., the systems subject of U.S. patents No. 4,136,566 (Christensen), 4.302,970 (Snitzer et al), 4,278,349 (Sander), 4,307,607 (Saaski et al), and the cryogenic temperature sensor described in NASA Technical Briefs, p.55, August, 1981). All of these systems are based on a temperature-dependent light attenuation.

Other sensor systems based on variable light attenuation and designed to measure a variety of measurands include the ones described in U.S. patents No. 4,356,448 (Brogardh et al.), 4,433,238 (Adolfsson et. al.), and 4,523,092 (Nelson). There are many others, but they fall within the same category of attenuation sensors covered by these references.

Fiber optic sensing techniques are especially suited for distributed sensing and for the multiplexing of a multiplicity of discrete sensors, and considerable interest has developed in recent years in these applications. A comprehensive review has been published recently (J.P. Dakin, J. Phys. E: Sci. Instrum 20, 954 (1987)), which discusses many approaches suggested or under development for these purposes. Some of these methods and approaches were first disclosed after the filing of the original application (serial No. 405,732) of which this is a Continuation in Part. OTDR techniques seem to be most extensively investigated, mainly coupled to the measurement of Rayleigh-backscattered light, but Ramen and fluoresence variants have also been proposed. An anti-Stokes Raman technique has been proposed for measuring temperature (Dakin et. al., Electron. Lett. 21 569 (1985)) based on the temperature-dependent occupancy number of a vibrationally excited level in a glass. The method provides signals which are orders of magnitude weaker than a method, also based on a temperature-dependent occupancy number of a vibrationally excited molecular level, subject of said original application serial No. 405,732 and using fluorescence conversion, and can be regarded as a less sensitive variant of said earlier invention. A recently proposed fluorescence technique proposed by Dakin, mentioned in said review article, is based on temperature-dependent changes in the fluorescence spectral distribution of some fluorescent dyes, in contrast to the methods of this invention, which do not require any temperature-dependent change in any fluorescence property and can, therefore, be implemented with most dyes.

A method for measuring distributed forces has recently been proposed by Faries and Rogers and discussed in another review article (A.J. Rogers, J.Phys. D: Appl. Phys. 19 2237 (1986)), based on the effect of force-induced changes of the polarization properties of single mode fiber on the stimulated Raman gain, under intense 'pumping' optical pulses, from sensing points along the optical fiber. The method has the disadvantage (among others) that polarization changes at one point along the fiber affect the polarization properties of the fiber along the rest of its length, and the results are thus difficult to interpret.

Macedo et al. (U.S. patent No. 4,342,907 describe an interesting OTDR-based system for the measurement of distributed forces acting at different pre-determined points along a fiber optic cable. These forces divert a fraction of the intensity of the interrogating light propagating along the fiber from the fiber

core into the cladding. This diverted light is removed by a coupler mechanically attached to the cable at each sensing point and transferred either to a second fiber optic cable (the return light guide) by means of another coupler, which directs this light to a photodetector in the OTDR device, or reflected back by an external detector into the same fiber optic cable towards the OTDR device. While the system has the advantage that it produces optical signals which are a linear function of the Intensity of the light forced out of the core, and are free of the baseline background of the interrogating light intensity, it is mechanically and optically complex, requiring at least one directional coupler per sensing point, and is unsuitable for detecting or measuring forces at points other than pre-determined ones.

It is an object of the present invention to provide methods and devices which eliminate or minimize the sources of error discussed above, said methods and devices producing both a single beam and a reference beam from a single light source, whether this be a broad band or a narrow band or monochromatic source, carrying both beams simultaneously through a single fiber to a single photodetection station, and separating, measuring and ratioing by simple means the electrical signals generated at the photodetection station by both the signal beam and the reference beam.

It is another object of this invention to provide a simple method for measuring directly and accurately small attenuations of an interrogating light beam produced by the action of a measurand, by generating a signal light intensity proportional to said attenuation and free of the intensity of the interrogating light incident on or transmitted by the sensor.

Still another object of the present invention is to provide new methods and devices for the measurement of diverse measurands at a plurality of remote locations simultaneously or quasi-simultaneously, using a single excitation light source and a single photodetector, with the individual probes attached to a single unbroken optical fiber, said measurements being only minimally affected by fluctuations of the intensity of the interrogating light beam, fiber losses or detector drift.

Yet another object of the present invention is to provide a long unbroken optical fiber as a distributed sensor, said fiber being sensitive to both mechanical forces and temperatures acting at different points along the fiber, and associated devices for the accurate measurement of the location and magnitude of said distributed temperatures and mechanic forces.

Other objects of the present invention will in part by apparent from the following discussion and will in part appear hereinafter.

<u>Brief Summary of the Invention</u>

These and other objects are accomplished by using so-called intensity sensors in a new manner whereby, in a preferred embodiment of the invention, interrogating light is launched into the core of an optical fiber probe for a measurand, wherein a fraction α of its initial intensity is removed from the core, the value of α being an indicator of the value of the measurand. Instead of discarding this removed fraction as in the prior art and estimating its value <u>indirectly</u> from the light intensity $P_o(1-\alpha)$ transmitted by the probe, the removed light is captured and <u>processed</u> into an optical signal separable from the transmitted interrogating light and from signals from measurands acting simultaneously at any other point(s) on the fiber, but carried <u>by the same fiber</u> to photodetection station, so that both the intensities of the transmitted interrogating light <u>light beam</u> and that of said removed fraction α, the value of α being an indicator of the value of the physical parameter, can be measured to give a ratiometric (referenced) reading of the value of the measurand, unaffected or only minimally affetced by fluctuations of the intensity of the interrogating light, fiber losses or detector drift. The processing of α into a separable, directly measurable signal, can be effected either in the optical spectral domain, by luminescence or Raman conversion into a light of different wavelengths from those of the interrogating light, or in the time domain, using pulsed or AC-modulated interrogating light and processing said fraction α into a signal which arrives at the photodetector either at a different time or with a phase shift relative to the interrogating light. An important feature of the invention is that the sensing materials it uses can be homogeneously incorporated into components of long optical fibers, allowing the measurement of temperatures and/or forces distributed over many locations, simultaneously and with a single fiber probe.

In contrast to prior art sensing methods using luminescent materials, the luminescence conversion techniques of this invention do not require any change in the luminescence spectral distribution, quantum efficiency or decay time of the sensor materials.

Definitions and Symbols

Within the context of this application, I am using the following definitions:

Light: optical radiation, whether or not visible.

Vibronic material: any material whose molecular electronic ground level comprises a plurality of vibrational sublevels with energies higher than that of the lowest occupied level of the material.

Vibronic level: a vibrational sublevel of the electronic ground state of a vibronic material, having an occupancy number which increases with increasing temperature.

Luminescence converter: a material which absorbs light and emits at least part of the energy thus absorbed as light at least part of the intensity of which is emitted at wavelenghts different from of the absorbed light.

Raman converter: a material which, when illuminated with light of any wavelength, scatters a fraction (usually small) of said light of a photon energy different from that of the illuminating light by an amount approximately equal to the energy of a vibrational quantum of said material.

Occupancy number of an energy level (or sublevel): the fraction of the molecules or ions of the material occupying said energy level (or sublevel).

Population Inversion: a condition in which the occupancy number of an electronically excited, emissive energy level, is greater than that of a lower level to which the excited molecules or ions decay through a radiative transition.

Measurand, or physical variable, or physical parameter: any physical property which can change in value. Examples: temperature, force, flow rate, level, position, and the like.

Interrogating Light: Light launched into the fiberoptic system and which is modulated by the physical parameters being measured.

Excitation light: interrogating light which generates a luminescence or Raman-shifted light of an intensity determined by the value of the measurand.

Force: any action which, on an optical fiber, affects the transmission of light along it. Examples: stress, pressure, sound waves, and the like.

λ_s: a wavelength of interrogating light within an absorption band of a sensing probe of this invention, used for sensing a force or forces acting on the probe.

λ_v: a wavelength of interrogating light at which the absorption coefficient of a sensing probe is temperature-dependent.

λ_f: a wavelength or wavelengths of light generated at a sensing probe by the interrogating light, different from the wavelength(s) of the interrogating light.

α : the fraction of the intensity of an interrogating light attenuated within a sensing probe at a sensing point.

α_s and α_v: fractions of the intensity of an interrogating light of wavelengths λ_s or λ_v, respectively, attenuated within a sensing probe at a sensing point.

Effective Optical Path Length of a Light Guide: the product of the actual path length of the light guide times its index of refraction.

Sensor: a probe or any other object which undergoes an observable change of a measured quantity under the effect of a physical variable.

Cladding: a light-guiding region surrounding a fiber core, whether or not it is in physical contact with the core, and regardless of the value of its index of refraction.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an energy flow diagram, at the molecular level, of a class of luminescent materials useful for measuring temperature according to this invention.

FIG. 2 shows the temperature dependence of the normalized fluorescence intensities of three organic dyes useful for measuring temperature according to this invention.

FIG. 3 is an energy flow diagram, at the molecular level, of another class of luminescent materials useful for measuring temperature according to this invention.

FIG. 4 illustrates a distributed optical thermometer according to this invention.

FIG. 5 illustrates the principles of anti-stokes Raman thermometry.

FIGS. 6 and 7 describe two optical fibers useful for practicing this invention, having a luminescent cladding.

FIGS. 8, 8A and 8B illustrate an arrangement for the measurement of distributed forces using optical

fibers having two light-guiding regions of different effective optical path length.

FIG. 9 represents a device for measuring distributed forces and temperatures according to this invention, using a single continuous optical fiber probe.

FIG. 10 shows a system for measuring distributed parameters on a single optical fiber using an AC-modulated C.W. light source, by phase angle division multiplexing.

FIG. 11 illustrates the principles of distributed sensing with single long fibers using optical 'pumping' and amplification of counterpropagating light.

FIG. 12 shows a distributed thermometer using a Nd(III)-doped glass optical fiber.

FIG. 13 illustrates a device for measuring distributed forces and temperatures with a single long optical fiber probe, using stimulated light amplification processes.

FIG. 14 illustrates a twin-core fiber suitable for sensing distributed forces and temperatures according to the invention.

FIG. 15 illustrates an optical fiber probe for the measurement of distributed temperatures, having a central core with a temperature-dependent numerical aperture.

FIG. 16 illustrates a two-dimensional tactile sensor according to this invention.

FIGS. 17, 17A and 17B illustrate fiberoptic keyboards according to this invention.

FIGS. 18 and 19 illustrate sensor fibers suitable for concentrating the optical powers of interrogating light into waveguiding regions where stimulated emission is generated.

FIG. 20 illustrates a light-difussing photo-irradiation probe for medical applications, capable of measuring its own temperature according to the teachings of this invention.

FIG. 21 is a schematic representation of a system for the sequential multiplexing and transmission of signals from electronic sensors on a continuous length of optical fiber.

DETAILED DESCRIPTION OF THE INVENTION

1.0 The Direct Measurement of Small Optical Attenuations Caused by Physical Variables.

In fiber optic sensing technology, optical attenuations are conventionally measured by indirect techniques. As the following example shows, such approach is not suitable for the measurements of small attenuations. Suppose that one is measuring temperature with an optical probe characterized by a temperature-dependent optical absorption coefficient at a wavelength λ_v. The optical density of the probe is low enough that, at a temperature of 300 kelvins (K), the probe absorbs a fraction α_v equal to 0.0100 of the power P_o of the interrogating light at that wavelength. The fraction α_v is not measured directly in the prior art in optical sensors. What is measured is the power P of the light transmitted by the probe. This is, disregarding scattering or other losses, equal to 0.9900 P_o. The value of α_v is derived from the difference $(P_o-P)/P_o$. Assume now that at 300 K the temperature coefficient of α_v is equal to 1.67 percent per K, that is, a temperature increase of 1K increases α_v by 1.67 percent. But one measures P, not α_v, and when α_v changes by 1.67 percent P changes by only 0.017 percent, a change of less than 2 parts per 10,000. Such a small change is difficult to measure accurately with ordinary photometric equipment.

Using the principles of this invention, one can measure α_v directly, and obtain an actual, directly measurable light intensity which does vary by 1.67 percent per kelvin. To do this, one uses a probe as described in the preceding paragraph, with the additional characteristic that the absorbed light of wavelength λ_v is converted by the probe into luminescence light having wavelengths λ_l different from λ_v. The intensity of this luminescence light, I_l, will then be an approximately linear function of α_v according to the relation

$I_l = P_o \alpha_v \phi (\lambda_v/hc)$ photons. sec^{-1}

where ϕ is the luminescence quantum efficiency of the probe material;

h is Planck's constant; and

c is the velocity of light in a vacuum.

If P_o is kept constant, then

$I_l = B \alpha_v$ photons. sec^{-1}

where B is a constant.

It is important to be able to measure small attenuations accurately, especially with multiplexed or distributed sensors, in which the attenuation of the interrogating light per sensing point must be kept low.

The above method is useful for increasing the accuracy of measurements from any kind of optical attenuation, not just attenuation by absorption. For example, microbending sensors work by forcing a

fraction of the intensity of the interrogating light propagating along the core of an optical fiber out of the core and into the fiber cladding. According to the teachings of this invention, one can incorporate a luminescent material or a Raman scattering material into the cladding and convert the light entering into the cladding under the action of the microbending force into either luminescence light or Raman-shifted light, the intensity of which is directly proportional to the fraction α removed from the core. One can then guide the converted radiation back along the same fiber to the photodetection station.

Alternatively, one can carry the fraction α through a fiber cladding, without luminescence conversion but rendered separable from the interrogating light being propagated through the core by the time domain separation technique described in section 3.2 hereinafter. The spectral or temporal separation of the signals from the interrogating light, plus signal intensities which are orders of magnitude stronger than Rayleigh-backscatter signals, permit the multiplexing of a much greater number of sensing points on a single sensing fiber than is possible with the prior art, for the same intensity of the interrogating light and the same photodetector.

2.0 SPECIFIC APPLICATIONS

2.1. Fiber Optic Temperature Sensors

The teachings discussed above can be used as a basis for constructing novel sensors with greatly enhanced performance compared to the prior art. As discussed above in the section "Description of the Prior Art", a number of fiber optic temperature sensors are based on optical transmission measurements of a temperature-dependent light absorption. In this section I describe improved sensors using vibronic materials and luminescence conversion of a temperature-dependent absorbed fraction of the intensity of the interrogating light, and present a theoretical analysis of some physical systems suitable for use in practical embodiments. The analysis is deliberately oversimplified to emphasize the aspects most relevant to the invention. It is not claimed that the quantitative relationships are followed rigurously in all practical cases.

The sensors are based on luminescent materials operated according to the principles described and illustrated with reference to FIG. 1. The luminescent material has a ground electronic energy level which comprises vibronic levels 40, 41, 42, 43 and other levels which, for the sake of simplicity, are not shown. The lowest excited electronic level comprises vibrational sublevels 50, 51, and other vibrational sublevels not shown. The vertical arrowed line 60 represents an optical electronic transition produced by the absorbed excitation light, from level 42 to vibrational sublevel 50, which have fixed energies E_v and E_s, respectively, relative to level 40.The length of line 60 corresponds to the photon energy of the optical transition and, hence, to the specific wavelength λ_v of the excitation light. This wavelength obeys the relation $\lambda_v = hc/(E_s-E_v)$, where h is Planck's constant and c is the velocity of light in a vacuum. The wavelength λ_v can excite only molecules occupying vibronic level 42 and, to a smaller extent, molecules occupying slightly higher levels, the excitation of which is represented by the dotted vertical line 61. Luminescence emission occurs from sublevel 50 to the vibronic levels of the ground electronic level., said emission represented by lines 70, 71, 72 and 73. As shown in FIG.1, a considerable spectral portion of the emission occurs at photon energies higher (and wavelengths shorter) than that of the excitation light, and is commonly referred to as anti-Stokes luminescence.

In practice the vibronic material is often used as a solid solution, glassy or crystalline, in a transparent host material, said solid material constituting the temperature probe. The concentration of the vibronic material and the dimension of the probe along the direction of the illuminating light are chosen so that the probe absorbs only a fraction α_v of the nearly monochromatic excitation light within the temperature range of operation, and transmits the rest. The absorbed fraction obeys the following relation:

$$\alpha_v = 1 - 10^{-\epsilon c_0 d (N_{42}/N)} \quad (1)$$

where ϵ is the molar decadic absorption coefficient of the molecules occupying the vibronic level 42;
c_0 is the total molar concentration of the vibronic material;
d is the length of the sensor in the direction of the incident excitation light;
N_{42} is the number of molecules of the vibronic material occupying vibronic level 42; and
N is the total number of molecules of the vibronic material.

The ratio N_{42}/N essentially follows the relation

$$N_{42}/N = f^{-1}.\exp(-E_v/kT) \quad (2)$$

where f is the so-called partition coefficient of the molecular system, k is the Boltzmann constant, and T is the absolute temperature. The expression $c_0.f^{-1}\exp(-E_v/kT)$ is essentially the effective molar concentration

of the molecules of the vibronic material occupying the vibronic level 42, and the quantity $10^{-\epsilon c_0 d(N_{42}/N)}$ represents the fraction of the illuminating (interrogating) light which is transmitted by the probe, assuming no scattering and/or reflection losses, and equal to $(1-\alpha_v)$.

At optical densities no greater than 0.02, α_v is approximately given by

$\alpha_v \approx 2.3\ \epsilon c_0 d f^{-1} \exp(-E_v/kT)$ (3)

At optical densities greater than 0.02 the relationship between α_v and the Boltzmann factor $\exp(-E_v/kT)$ becomes less linear, but equations (1) and (2) are still valid, and the method can be used at high, low or intermediate optical densities.

The luminescence intensity I_l generated by the light absorbed by the sensor obeys the relation

$I_l = P_o(\lambda_v/hc)\alpha_v\phi$ photons. sec^{-1} (4)

where P_o is the radiant power, in watts, of the incident excitation light, and

ϕ is the luminescence quantum efficiency of the vibronic material.

Probes made from materials having high ϕ values can produce large signal-to-nois ratios even with optical densities lower than 0.01, provided thet the optical system has at least a moderately high collection efficiency for the generated luminescence. Such efficiency is easily obtainable with state-of-the-art fiber optic systems.

The sum of the light intensity absorbed and the light intensity transmitted by a clear medium is constant. It follows, therefore, that as the absorbed fraction α_v increases with an increase in temperature according to equation (3), the intensity of the transmitted fraction must decrease accordingly. Since, according to equation (4), the intensity of the luminescence light is proportional to α_v, it follows that the ratio of the intensity of the luminescence light to that of the transmitted light increases with an increase in temperature, and the ratio can be used as a temperature indicator. The ratio eliminates or minimizes any sources of error associated with fluctuations of the intensity of the illuminating light and fiber or connector losses.

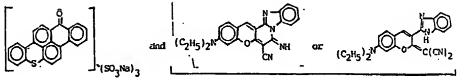
The temperature coefficient of the luminescence intensity follows approximately the relation

$(1/I_o)(dI_l/dT) = E_v/kT^2$ (5)

where I_o is the luminescence intensity at a chosen reference temperature. For example, a material with a value of E_v of 1200 cm^{-1} has a coefficient of about two percent per kelvin at a temperature of 295 K.

Equations (3) to (5) show that the method of the preceding paragraphs requires only temperature-dependent change in the optical absorption coefficient of the luminescent sensor material at wavelengths corresponding to photon energies lower than the energy E_s of the excited emissive level. This property is shared by virtually all solid and liquid luminescent materials. The method does not require any temperature-dependent changes in the luminescence quantum efficiency, spectral distribution or decay time. Therefore, and in contrast to all other prior art methods, it can be implemented with most luminescent materials.

Experimental tests of equations (3) to (5) have been carried out with liquid solutions of three different dyes dissolved in dimethyl sulfoxide (DMSO). Two of the dyes, dye I and dye II are represented by the chemical structures



I II

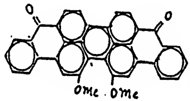
Dye I is the sulfonated derivative of Hostasol Red GG (American Hoechst Corp.). Dye II has been described in U.S. Patent No. 4,005,111 by Mach et. al. The third dye was the well known Rhodamine 6G (R6G). The dyes were dissolved in DMSO at concentrations of the order of 10^{-4} Molar and excited with light from a He-Ne laser (λ = 633 nm) in a square cuvette. The fluorescence intensity was monitored at the wavelength of 612 nm, shorter than the wavelength of the excitation light. The experimentally measured fluorescence intensities I_l were measured as a function of the absolute temperature T. Plots of I_l v. T^{-1} are shown in Figure 2 for the three dyes. The behavior predicted by equations (3) and (5) was confirmed. The slopes of the lines drawn through the experimental points give E_v values of 1380, 1355 and 1890 cm^{-1} for dyes I, II and R6G, respectively. When these values are added to the excitation photon energy of 15803 cm^{-1}, one obtains E_s values of 1.72×10^4 cm^{-1} for dyes I and II, and 1.77×10^4 cm^{-1} for R6G. These values are in good agreement with the E_s values determined from the fluorescence spectra of these dyes.

The validity of equations (3) and (5) is independent of whether the sensor is a liquid or a solid. Although

the laboratory reduction to practice was done with liquid solutions of these dyes, solid plastic solutions are preferred for practical measurements. Examples of suitable plastics are polystyrene, polymethyl methacrylate, polyurethanes and silicones.

An important advantage of this method for measuring temperature is that the value of E_v, which determines the optimum temperature range of operation, can be chosen and varied at will over a continuum of values simply by choosing, for any given vibronic material, the photon energy of the excitation light relative to the energy E_s of the excited emissive level (sublevel 50 in Figure 1). Thus, a single sensor can be used for measuring temperature over a wide range, from cryogenic temperatures up to the highest temperatures which the sensor can withstand without deterioration or severe thermal quenching of its luminescence. An additional advantage derives from the fact that there are many luminescent vibronic materials having absorption and luminescence spectra over a wide spectral region from the ultraviolet to the near infrared. One can choose, therefore, the wavelength region most suitable to one's needs. For instance, if it is required to transmit the optical signal over long distances via an optical fiber, one could choose a material with absorption and luminescence bands at wavelengths longer than 600 nanometers (nm).

Examples of vibronic materials suitable for measuring temperature according to this invention are plastic-soluble fluorescent dyes, like dyes II and R6G used for obtaining the data of FIG. 2. Other preferred dyes are those with excitation and fluorescence bands within the spectral region in the red and near infrared for which efficient and inexpensive light-emitting diodes (LED's) and laser diodes (LD's) are commercially available. These include dyes of the violanthrone family, including but not limited to the dye having the Color Index designation of Vat Green 1, having the chemical structure



The solubility of these dyes in plastics can be increased by attaching to them solubilizing substituent groups like long chain or branched chain alkyl radicals. In dye Vat Green 1, for instance, the methyl (Me) radicals shown can be replaced by tert-butyl or longer chain radicals by techniques well-known to chemists.

Other vibronic materials suitable for measuring temperature according to the teachings of this invention include inorganic crystals doped with chromium(III) or other transition metal ions like nickel(II), cobalt(II) or vanadium(II).

Another class of vibronic materials, also suitable for use as temperature sensors according to this invention, are described with reference to Figure 3, which shows a simplified molecular energy level diagram somewhat similar to that of Figure 1. What is different is that the emissive energy level is different from the level which is directly excited by the excitation light. Referring to Figure 3, excitation of molecules occupying a vibronic level proceeds in the same manner as shown in Figure 1 for the materials described hereinbefore. levels 40A, 41A, 42A, 43A, 50A and 51A are similar to levels 40, 41, 42, 43, 50 and 51, respectively. The same digits in both figures indicate the similarity of the excitation processes, and the A's were added to the levels of Figure 3 to indicate that these levels belong to a different class of vibronic materials. The difference is that in this case the optically excited level 50A transfers at least a major part of its excitation energy, via a radiationless decay represented by the wavy line 55, to the lower level 56, of the same or of a different molecular species. Luminescence occurs from level 56 to a lower level 57 or to any other lower-lying levels which may or may not include any of the levels 40A, 41A, 42A or 43A. Examples of this class of vibronic materials include virtually all Triplet → Singlet phosphorescent dyes, luminescent chelates of terbium(III) and europium(III), and some solid solutions of inorganic vibronic materials co-doped with other luminescent centers. Examples of the latter are crystalline or glassy materials co-doped with chromium(III) and neodymium(III), in which chromium(III) ion absorb the excitation light and transfer their excitation energy to the neodymium(III) ions, causing them to luminesce.

Some sensor materials can behave either according to the model of Figure 1 or the model of Figure 3, depending on the temperature range in which they operate. For example emerald, a chromium(III)-doped beryl, behaves according to the model of Figure 1 at temperatures higher than ambient, and according to the model of Figure 3 at cryogenic temperatures.

Two other classes of materials suitable for the practice of this invention are:

(a) luminescent lanthanide ions dissolved at relatively high concentrations in crystalline or glassy hosts, and having at least one electronic energy level which can be thermally populated to a measurable extent at the temperatures being measured, and

(b) luminescent semiconductors with a temperature-dependent absorption edge wavelength. Both casses of materials are characterized by an absorption coefficient which, within a relatively narrow spectral region, increases approximately exponentially with increasing temperature in essentially the same manner as with the vibronic materials described hereinbefore. Therefore, they are used in essentially the same manner and with the same methods as disclosed above.

In the above-described embodiments the luminescent centers had a temperature-dependent absorption coefficient to light of photon energy lower than that of the electronic level being excited. These centers are designated herein as A centers. One preferred procedure for referencing the signals from these centers is to incorporate in the same medium other luminescent centers, designated herein as B centers, the absorption coefficient and luminescence efficiency of which are approximately independent of temperature within the temperature range being measured, when excited with light of the same wavelength λ_v as the A centers, and the luminescence of which is emitted in a spectral region different from that of the A centers. If one divides the luminescence intensity emitted by the A centers by a luminescence intensity emitted by the B centers, the ratio so obtained is a unique function of temperature. This referencing technique is discussed further hereinafter in connection with continuous, distributed temperature sensors using a single long, unbroken temperature-sensing optical fiber.

When using a non-crystalline sensor material, it is convenient to make it the core of an optical fiber segment, with an appropriate cladding around the core, for easy connection to an optical fiber waveguide.

2.2. A Distributed Temperature Sensing System

The advantages of the temperature sensing of this invention, discussed in the preceding section, can best be appreciated by its adaptability to measure temperatures in a multiplicity of locations simultaneously, with the probes at each location being part of a series array of sensors along a fiber-guided light path. Such an application requires accurate measurements of small changes in the intensity of the light propagating along the array, as the multiplexing of many light-absorbing probes along a single light path requires that each probe absorb only a relatively small fraction of the intensity of the interrogating light. One suitable embodiment uses individual probes, conveniently in the form of optical fibers, spliced at different locations into a long optical fiber guide. A logical extension of this concept is to dope the whole continuous length of a long fiber with the light-absorbing luminescence converter. Such an embodiment is a preferred one when the number of sites to be monitored is large, or when checking for hot spots along a continuous path, for example along the windings of a large electrical transformer. As described above, one can measure small optical absorptions directly by converting the fraction of the intensity of the light which is absorbed into luminescence or Raman emission.

If one uses as a light-absorbing material a fluorescent dye with a fluorescence decay time of the order of nanoseconds (characteristic of most fluorescent dyes), then one can use OTDR techniques for converting any light absorbed at any point along the fiber length into a fluorescence light intensity free of the baseline background of the interrogating light. If, for example, a resolvable fiber segment length absorbs one percent of the interrogating light intensity at 300 K, and the temperature coefficient of the absorption is 1.2 percent per kelvin, the fluorescence intensity will change by 1.2 % per kelvin, while the intensity of the transmitted light, as measured by Rayleigh backscattering, will change by only about one part per 10,000.

In a practical embodiment one must be able to measure both the temperature and the location of any hot or cold spot. Location information can be obtained by standard OTDR techniques, from the time of arrival of the fluorescence light pulses at the electro-optic unit, relative to the time of launching of the interrogating light pulse into the fiber. The following relation holds:

$d = 0.5\, t\, c/n$

where d is the fiber distance from the electrooptical unit (where the interrogating light pulses were launched);

t is the time of arrival of the fluorescence light pulses;

c is the velocity of light in a vacuum; and

n is the index of refraction of the glass of the fiber core.

The temperature of the fiber at any distance d from the electrooptic unit is determined from the intensity of the fluorescence pulse.

The spatial resolution of the measuring system is determined by the risetime and duration of the

interrogating light pulses, and by the fluorescence decay time of the fluorescent material. With fluoresence pulses with a duration of 10 nanoseconds one can obtain spatial resolutions of about 1 meter or better.

Two alternate embodiments are described below:

In the first embodiment, applicable when the fiber length does not exceed about 100 meters, the fiber consists of a plastic core having the fluorescent dye dissolved therein, and a plastic cladding with an index of refraction lower than that of the core, but with a temperature coefficient of said index of refraction similar to that of the core. Only minute concentrations of the dye are needed, so there is a large number of efficient fluorescent dyes availabe, including dyes II and R6G subject of FIG 2. Since virtually all plastic-soluble fluorescent dyes can be used for the practice of the invention, it is convenient to use those which can be interrogated with light from inexpensive LED's or laser diodes, and which have good stability. Dyes of the violanthrone (dibenzanthrone) family, including Vat Green 1, have these characteristics.

For accurate measurements it is necessary to provide a reference signal. The intensity of the Rayleigh-backscattered light can be used for this purpose. The ratio of the intensity of the dye fluorescence to that of the Rayleigh-backscattered light provides a reliable indication of the temperature at each resolvable fiber length.

If longer lengths of the temperature-sensing fiber are needed, the second embodiment is preferable. In this case one uses an optical fiber having a core made of low-attenuation glass, for instance pure silica, and the fluorescent dye is dissolved in a transparent plastic cladding. The index of refraction of the plastic cladding is lower than that of the core, and excitation of the dye fluorescence is accomplished by evanescent wave coupling. Since the light paths of both the interrogating light and the fluorescence light are through low-attenuation glass, light signals can be collected over much longer distances than possible from an all-plastic fiber. Signal referencing can be obtained by co-dissolving in the plastic cladding a second fluorescent dye the absorption coefficient and fluorescence efficiency of which are essentially invariant over the temperature range to be measured. The relative fluorescence intensities from the two dyes uniquely define the temperature of the fiber at the measured location. The second fluorescent dye (the reference dye) can be chose from any fluorescent dye soluble in the plastic cladding and having a fluorescent level with an energy no higher than the photon energy of the interrogating light.

A suitable embodiment of a device (essentially an optical time-domain reflectometer with an added fluorescence channel) for performing distributed temperature measurements with either of the above fiber embodiments is shown schematically in FIG. 4. The light source 10 is driven to produce interrogating light pulses with a duration of about 10 to 30 nanoseconds and a wavelength λ_v. These light pulses are injected into the fiber segment 11 and, through the optical fiber coupler 12, into the temperature-sensing fiber 13. At any point along the fiber, each interrogating light pulse produces a fluorescence light pulse with an intensity determined by the temperature at that point, and a reference pulse at a different wavelength from that temperature-dependent pulse. In the case of the plastic fiber the reference pulse is the intensity of the Rayleigh-backscattered light. In the case of the fiber with the glass core and fluorescent plastic cladding, the reference pulse is the fluorescence light pulse produced by the co-dissolved second fluorescent dye, this dye having a temperature-independent optical absorption coefficient at the wavelength of the interrogating light. Both the temperature-dependent light pulses and the reference pulses are transmitted by the optical fiber to the electro-optical unit and, through optical coupler 12 and fiber segments 14 and 15, to photodetectors 16 and 17. The photodetectors are made spectrally selective, one to the temperature-dependant optical pulses, and the other to the reference pulses, by means of narrow band-pass optical filters applied to their windows. The time of arrival at the photodetectors of the optical pulses generated at any point along the fiber, relative to the time of generation of the interrogating light pulse at the light source, defines the location along the fiber where the optical pulses are generated. The ratio of the photoelectric signal from the fluorescence generated by the temperature-dependent absorption to the reference signal is an indicator of the temperature at that point along the fiber. When such ratio is recorded as a function of the fiber distance from the fiber tip into which the interrogating light pulses are launched the above-background temperatures appear as peaks, and the below-background temperatures appear as depressions in graph 4A.

2.3. The Measurement of Temperature Distributions by anti-Stokes Raman Scattering.

The preceding sections described how one can use a material for measuring temperature, by causing it to convert a temperature-dependent fraction α_v of the intensity of illuminating light of pre-selected avelength λ_v into light emitted at a wavelength different from λ_v. The above cited anti-Stokes Raman technique by Dakin et al., Electron. Lett. 21, 569 (1985), can be regarded as a special case of this general technique. It also uses a temperature-dependent excitation of molecules occupying thermally populated vibronic levels,

except that the optical excitation is to a virtual energy level rather than to an actual one. The process is illustrated by FIG. 5. As in the case of luminescent vibronic materials, the occupancy number N_{42} is determined by the Boltzmann factor $\exp(-E_v/kT)$. The above equations (2) and (5) are also approximately obeyed. But the fraction α_v of the interrogating light which can be emitted as Raman-scattered light is usually orders of magnitude smaller.

3.0. The Measurement of Distributed Forces with a Single Unbroken Fiber Probe.

Mechanical forces acting on an an optical fiber, especially microbending forces, usually cause an attenuation of light being transmitted through the fiber core, by deflecting a fraction of the intensity of this light out of the core and into the fiber cladding. If such forces are acting on a plurality of points on a long fiber, or at a single but unknown location on it, they can usually be measured by Optical Time Domain Reflectometry (the abbreviation OTDR is used herein both for the method and for the device used for implementing it). The method consists of launching interrogating light pulses with a duration typically of the order of nanoseconds (ns) into the fiber core, and measuring the intensity of the Rayleigh-backscattered light pulses as a function of fiber distance from the fiber tip at which the interrogating light pulses were launched. Any force on the fiber which causes an attenuation of the intensity of the interrogating light pulses (for instance a microbending force) is revealed as a discontinuity in the backscatter intensity versus distance decay curve. The time of arrival of the Rayleigh-backscattered pulses, relative to the time of launching of the interrogating light pulses, defines the location along the fiber where the force is acting, and the intensity of the backscattered pulses indicates the magnitude of the force.

A serious shortcoming of this method is that it 'throws away' the deflected light to be measured, and instead estimates its magnitude indirectly from a difference between two usually much larger, but still weak and noisy backscatter signals. Rayleigh scattering is an inefficient process, producing intensities at the photodetector which are typically 50 or more dB down from the forward interrogating light intensity at any 1 meter length of fiber. These indirect measurements are, then, plagued by a relatively large amount of baseline noise.

The teachings of this invention provide a method and associated devices for the measurement of force distributions on optical fibers, as well as temperature distributions. The method and devices of this invention are capable of producing, in the measurement of forces, signals stronger by orders of magnitude than those obtainable from Rayleigh-backscatter measurements, for the same extent of optical attenuation and with the same intensity of the interrogating light. The method consists of converting the fraction of the intensity of the interrogating light which has been deflected into the fiber cladding into a signal separable from the interrogating light transmitted through the fiber core. This separation can be achieved either in the optical wavelength domain, by luminescence or Raman conversion, or in the time domain, as illustrated in the following embodiments.

1st Embodiment.

This embodiment uses a fiber shown schematically in FIG. 6, consisting of a glass core 1 with an index of refraction n_1 and a cladding 2 with an index of refraction n_2 lower than n_1. Around cladding 2 there is a second cladding, concentric layer 3, containing fluorescent centers absent in either the core or in cladding 2 and having a luminescence decay time of the order of nanoseconds, this cladding having an index of refraction n_3 not lower than n_2 and a thickness of a few micrometers. Around cladding 3 there is a third cladding 4 with an index of refraction n_4 substantially lower than n_3. Interrogating light pulses with a duration of the order of nanoseconds, having wavelengths within the absorption band of the fluorescent centers, are launched into the core 1 of the fiber, where they propagate along the fiber axis with a small attenuation caused by residual optical absorption with a coefficient ϵ and, usually to a larger extent, by Rayleigh light scattering with a coefficient β. At a point A along the fiber, the launched interrogating light pulses have an intensity P_o. After this point, and for a length L corresponding to the time resolution of the OTDR, the light intensity is attenuated by a fraction a_l. The power P_s of the Rayleigh-backscattered light pulses generated within the fiber segment of length L within the fiber numerical aperture $(NA)_s$ and sent to the photodetection station is given approximately by

$$(P_s/P_o \approx \tfrac{1}{2}\, a_l[\beta/(\beta+\epsilon)].[(NA)_s^2/4n_1^2]f_t \text{ watts} \qquad (6)$$

where the terms within the second square brackets define the fraction of the power of the scattered light captured within the solid acceptance angle of the fiber core, and f_t is the fraction of the power of this

captured light which is transmitted by the fiber along the optical path to the photodetector. The numeral aperture $(NA)_s$ is given by

$(NA)_s = (n_1^2 - n_2^2)^{\frac{1}{2}}$ (7)

An external force operating on this fiber segment and capable of producing a localized strain or any other microbending force will deflect a fraction α_s of the power P_o of the interrogating light propagating along the fiber core at that point into cladding 2, due either to fiber microbending or to the increase of the index of refraction n_2 of the glass cladding relative to that of the core, the value of α_s being determined by the magnitude of the force. Then P_s will be decreased by this fraction, and the change ΔP_s (the signal) will be given by the relation

$\Delta P_s = \alpha_s P_s$watts

It should be noted that the optical processes described above involve only core 1 and cladding 2 and are, therefore, unaffected by layer 3 or cladding 4.

Let us now look at what happens to the light forced out of the glass core 1 and into cladding 2. For this purpose, we must treat the fiber as having a second numerical aperture $(NA)_f$, for the generated fluorescence, defined as

$(NA)_f = (n_2^2 - n_4^2)^{\frac{1}{2}}$ (8)

Light entering cladding 2 at angles within $(NA)_f$ will be trapped and propagated along the fiber axis by total internal reflection from cladding 4 but, after a number of reflections determined by the absorption coefficient and concentration of the fluorescent centers in layer 3, will be absorbed by these centers and converted into fluorescence with a quantum efficiency ϕ. The fluorescence will usually be emitted at longer wavelengths than those of the absorbed interrogating light. The fraction P_f of the power of this fluorescence light which reaches the photodetector is given approximately by

$P_f \approx \frac{1}{2}\alpha_s P_o \phi \, [(NA)_f^2 / 4n_2^2] f_t^{'} (\lambda_s/\lambda_f)$ watts (9)

where $f_t^{'}$ is the fraction of the fluorescence power generated within $(NA)_f$ which is transmitted by the fiber along the optical path to the photodetector;

λ_s is the wavelength of the interrogating light; and

λ_f is the mean wavelength of the fluorescence light.

Let us now assume some typical values for some of the parameters in equations (6) and (9), for a fiber segment one meter long: $a_t = 2.3 \times 10^{-3}$

$[\beta/(\beta + \epsilon)] = 0.80$

$\phi = 0.70$

$f_t^{'} / f_t = 0.70$

$(NA)_s = 0.20$

$(NA)_f = 0.40$

$n_1 = 1.500$

$n_2 = 1.487$

$(\lambda_s/\lambda_f) = 0.90$

Stress or microbending forces which attenuate the intensity of the interrogating light by not more than a few percent will deflect into cladding 2 only optical rays within the numerical aperture $(NA)_f$ of the fiber, especially in view of the high value of $(NA)_f$ relative to $(NA)_s$. Thus, equation (9) applies, and one can determine from the above values of the relevant parameters that

$P_f/\Delta P_s \approx 975$

Fluorescence conversion of light forced out of the core of an optical fiber by stress or other forces can, thus, produce signals orders of magnitude stronger than those obtained from the decrease of the Rayleigh-backscattered light produced by the same forces. As a consequence of this, distributed sensing systems can be designed so that each sensing point attenuates a small fraction only of the intensity of the interrogating light propagating along the fiber at that point, thus allowing a given intensity of the interrogating light launched into the sensing fiber to interrogate, and produce strong signals from, a much greater number of sensing points than would be practical with a system based on Rayleigh-backscattered signals.

The above-described fluorescent claddings can be applied to maximize diagnostic information from various types of fibers, including multimode step index, graded index and single mode fibers. In the latter case, of course, only the interrogating light beam is single mode. Cladding 3 can be, for example, a clear plastic doped with an organic fluorescent dye.

Second Embodiment.

In the second embodiment the light forced out of the fiber core by a stress or microbending force is converted into Raman-scattered light at a wavelength different from λ_s. This requires a different fiber from that used in the first embodiment. The fiber consists of the same or similar glass core 1 as in Figure 6. Around this core is a glass cladding having a relatively high Raman-scattering coefficient, for example a silica glass doped with a high concentration of phosphorous pentoxide, P_2O_5, as Raman-active material. It is important that the fiber core does not contain the Raman-active material present in the cladding. Also, the cladding volume per unit length should preferably be greater than the core volume. Light forced out of the core and into the cladding is converted into Raman-scattered light. Generally, the Raman conversion process is less efficient than fluorescence conversion, so that the signal strengths are smaller than possible with fluorescence conversion, at least for fiber lengths of the order of a few meters.

Third Embodiment

The third embodiment is advantageous when the fluorescent material is an organic dye, and the dye can be dissolved in a transparent plastic cladding having an index of refraction substantially lower than n_2, the index of the glass cladding of Figure 6. This will become apparent from the following discussion.

Even the clearest plastics attenuate light by at least an order of magnitude more than the best fiber-grade glass. It is because of this fact that that the fluorescent layer 3 was specified to be only a few micrometers thick. If the diameter of cladding 2 is, for instance, 125 micrometers (a common value), then only a small fraction of the optical path of the fluorescence light is through a high loss material. But there is a better and simpler way to achieve this objective, as described below.

Fluorescence Conversion by Evanescent Wave Coupling

The force-sensing fiber of this embodiment is illustrated in Figure 7. It comprises the same core and the same cladding 2 of FIG. 6. Around cladding 2 there is a second cladding, coating 4′, made of a transparent plastic and having dissolved therein a fluorescent dye characterized by a high quantum efficiency, an absorption band in a spectral region comprising the wavelength of the interrogating light, λ_s, and a fluorescence decay time of the order of 10^{-8} seconds or shorter. The plastic has an index of refraction n_p low enough to produce a numerical aperture $(NA)_{lp}$ higher than 0.3, and preferably higher than 0.4, $(NA)_{lp}$ being defined by the relation

$(NA)_{lp} = (n_2^2 - n_p^2)^{\frac{1}{2}}$ (10)

Light entering cladding 2 from core 1 at angles greater than the critical angle θ_c for total internal reflection from coating 4′ will enter this cladding at least to a depth d_p known as the thickness of the evanescent layer, and defined as the depth over which the electrical field amplitude of the light waves decays to the value 1/e of its value at the interface between cladding 2 and coating 4′. The value of d_p is given by the relation

$d_p = (\lambda_e/n_2)/2\pi[\sin^2\theta-(n_p/n_2)^2]^{\frac{1}{2}}$ cm (11)

where θ is the angle of incidence of the light rays on the interface between cladding 2 and layer 4′ (this layer can legitimately be regarded as a second cladding). Only a small fraction of the intensity of the incident light will be absorbed per reflection but, by a proper choice of the concentration of the fluorescent dye, virtually the entire intensity of the light leaving the core at angles greater than θ_c can be absorbed over the length L of the resolvable fiber segmant. The generated fluorescence can be collected by the optical fiber with high efficiency, because the angular distribution of the fluorescence will favor the modes within the acceptance angle of the fiber (Lee et. al., Appl. Opt. 18, 862 (1979))

3.1 A Practical Device for Measuring Distributed Forces According to this Invention.

Distributed forces can be measured with the same electro-optical arrangement as that described with reference to FIG. 4, with the sensing fiber 13′ being either one of the fibers illustrated in FIGS. 6 or 7. The light source 10 is driven to produce interrogating light pulses of submicrosecond duration and wavelength λ_s within an optical absorption band of the fluorescent centers (fluorescent molecules or ions) in the applicable cladding. These light pulses are launched into the core of the sensing fiber, where they propagate along the fiber length. At any point along the fiber on which a mechanical force is acting, a fraction α of the intensity of the interrogating light pulses is deflected out of the core and into cladding 2, and is immediately

converted into fluorescence light pulses by the fluorescent centers in the applicable cladding (cladding 3 if the fiber of FIG. 6 is used, or the evanescent layer of cladding 4′ in the fiber of FIG. 7). Both the fluorescent light pulses and the Rayleigh-backscattered light pulses (from the fiber core) travel back to the electro-optical unit and, through the fiber optic coupler 12 and fiber segments 14 and 15, to photodetectors 16 and 17, which are made spectrally selective to the force-dependent fluorescence pulses and the Rayleigh-backscattered pulses, respectively. The ratio of the photo-electric signls from the two photodetectors is an indicator of the value of α and, hence, of the magnitude of the force. The time of arrival of the optical pulses at the photodetectors, relative to the time of launching of the interrogating light pulses, identifies the location of the force. The fluorescence light pulses are easily separable from the Rayleigh-backscattered pulses because of their different, generally longer, wavelengths.

3.2 The Measurements of Forces with Optical Fiber Probes Having Two Light-guiding Regions of Different Effective Optical Path Length.

In the embodiments of force-sensing systems discussed above, I have described how light deflected out of the core of an optical fiber under the action of a force can be processed into an optical signal separable from the light transmitted by the fiber core. In the above embodiments, signal separation is effected by converting the deflected light into spectrally separable light of different wavelengths from those of the interrogating light. Separation can also be effected in the time domain, by processing the pulsed or AC-modulated light deflected out of the core into a lighthaving different temporal characteristics from those of the interrogating light carried by the fiber core, without the need for wavelength conversion. A preferred embodiment of such a technique is described in the following paragraphs, with reference to FIGS. 8 and 8A.

The optical fiber 13A shown schematically in FIG. 8 comprises a single mode core 1 with an index of refraction n_1, a first cladding 2A around the core having an index of refraction n_2 such that the value of $(n_1^2 - n_2^2)^{\frac{1}{2}}$ does not exceed 0.15, a light-guiding region 3A around cladding 2A, having a graded parabolic or near parabolic index of refraction the peak value of which, n_3, is several percent higher than n_1, and an outer cladding 4A with an index of refraction n_4 lower than n_2. The fiber is used as a distributed force-sensing probe with a device represented schematically in FIG. 8A.

Referring to FIG. 8A, light source LS launches into the fiber core a train of interrogating light pulses with a duration of the order of 10^{-9} seconds or shorter, depending on the spatial resolution desired. At any point where a lateral force is acting on the fiber, a small fraction of the intensity of each interrogating light pulse is deflected out of the fiber core into light-guiding region 3A, where it is trapped by the graded refractive index distribution of this region and by the outer cladding 4A. Because n_3 is substantially higher than n_1, the effective optical path length of region 3A, (that is, its actual length multiplied by its index of refraction) is substantially longer than that of the core 1, so that the light deflected out of the core into region 3A arrives at the photodetector 16A at the distal fiber end after a resolvable interval t following the arrival of the interrogating light pulses carried by the fiber core. This interval identifies the location at which the deflection occurred, according to the relation

$t = (z/c)\,(n_3 - n_1)$ seconds (12)

where z is the fiber distance to the photodetector of the point where the the force was acting; and c is the velocity of light in a vacuum.

For example, if n_3 is equal to 1.553 and n_1 is equal to 1.46, then two sensing points one meter apart along the fiber will produce signals arriving at the photodetector about 3.1×10^{-10} seconds apart, assuming that the duration of the interrogating light pulse is not longer, and that region 3A does not introduce a serious pulse broadening. Since the light-guiding region 3A has a parabolic or near parabolic index profile, the broadening can be shown to be relatively low for some practical fiber lengths. The rms pulse broadening Δt is given aproximately by the relation

$\Delta t \approx [(n_3-n_1)/n_3]^2\,[n_3\, z/20.c.3^{\frac{1}{2}}]$ seconds (13)

For a z distance of 100 meters and the above assumed values for n_3 and n_1, Δt is approximately equal to 5.4×10^{-11} seconds. The actual dispersion may be somewhat greater because of some dispersion in the first cladding 2A, but spatial resolutions of the order of 1 meter should be obtainable in fiber lengths of about 100 meters. If numerous forces are acting at different locations along the fiber, their signals will arrive at the photodetector at different resolvable times. The intensities of the time-resolved signals will be indicators of the magnitude of the forces.

Another embodiment of a fiber with two light-guiding regions of different optical path length consist of a fiber wherein one of the two light-guiding regions has an actual path length different, for the same unit length of the fiber, from that of the other light-guiding region. An example of such embodiment is a fiber as

shown schematically in FIG. 8B, having a helical core 1A with an index of refraction n_1, a first cladding 2B around said core, having an index of refraction n_2 lower than n_1, and a second cladding 3B around the first cladding, with an index of refraction n_3 lower than n_2. When light pulses with a duration of 10^{-9} seconds or shorter are launched into the core of this fiber, and a lateral force deflects a fraction of the intensity of this light into cladding 2B, the cladding light pulses arrive at the photodetector before the light pulses propagated by the core. The interval t' between the core pulses and the cladding pulses follows the relation

$t' = (z/c)(n_1 C - n_2)$ seconds (14)

where C is the ratio of the actual optical path length of the helical core to that of cladding 2B. Another embodiment uses a straight core and a helical cladding around the core.

Optical fibers having a helical light-guide region tend to lose light at points other than those at which the forces to be measured are acting, so they are suitable for use in lengths not exceeding about 100 meters. For short fiber lengths, fibers with a helical light-guiding region have the advantage of better spatial resolution than fibers with both light-guiding regions straight, for the same duration of the interrogating light pulses.

4.0 The Measurement of Distributed Forces and Temperatures on a Single Unbroken Optical Fiber.

The fibers illustrated in FIGS. 6 and 7 can be used for measuring both forces and temperatures independently of each other, not only on the same fiber, but also on the same location on the fiber. A preferred embodiment of an OTDR device for carrying out such measurements is illustrated in Fig. 9. The sensing fiber 13B is the fiber of FIG. 7, except that cladding 4′ has two dyes dissolved in it, A and B, only one of which, dye A, has a temperature-dependent absorption coefficient when interrogated with light of wavelength λ_v. Dye B is used as a reference as taught in section 2.1.1. Temperature distributions are probed by launching short interrogating light pulses of pre-selected wavelength λ_v from light source 10A, through fiber optic couplers 12A and 12B, into both the core 1 and the first cladding 2 of the sensing fiber, and the temperature distributions are determined as already decribed (with reference to FIG. 4). Force distributions are probed by injecting, into the core 1 only of the sensing fiber, similarly short interrogating light pulses (with a duration of, for example, 10 to 30 nanoseconds, depending on the fiber length resolution desired) of pre-selected wavelength λ_s corresponding to a photon energy not lower than the energy E_s of the lowest vibrational sublevel of the emissive level of dye A, at which light absorption is much stronger than at the wavelength λ_v and is essentially independent of temperature over the temperature range of operation. Any cladding modes of the λ_s injected at the launch end of the sensing fiber will be essentially 'stripped' by dye A in cladding 4′, because of its much higher absorption coefficient for for light of this wavelength than for λ_v light. The intensity of the fluorescence pulses generated at any point along the fiber by the force-probing pulses will then indicate the magnitude of the force on the fiber at that point, essentially independent of temperature. Photodetector 16 receives the fluorescence signals from dye A generated, alternately, by the λ_s force-probing pulses and the λ_v temperature-probing pulses. Photodetectors 17 and 17A receive and measure, respectively, the Rayleigh-backscattered pulses for normalizing the force readings, and the dye B fluorescence pulses for normalizing the temperature readings.

5.0 The Measurement of Distributed Forces with an Optical Fiber Using an AC-Modulated C.W. Light Source

The ability of the optical fibers of this invention to produce relatively large positive signals from forces and/or temperatures affords a simple alternative to conventional Optical Time Domain Reflectometry (OTDR), which does not require the use of every short light pulses for measuring the location and magnitude of these parameters. The alternative method is illustrated by FIG. 10. The light source 10, which could be an inexpensive light-emitting diode (LED), is driven by a crystal-controlled oscillator 9 at a frequency preferably not lower than 100 kHz, to generate a sinusoidally-modulated interrogating light which is launched through the fiber coupler 12C into the optical fiber 13′. This fiber can be either one of the optical fibers illustrated in FIGS. 6 and 7. A small fraction of the intensity of the interrogating light is diverted by coupler 12A and optical fiber segment 14A into photodetector 16. When the interrogating light beam reaches a point P along the fiber where a force is acting, a relatively small fraction α of the intensity of the interrogating light propagating along the fiber core is forced into the glass cladding, and is then converted into fluorescence light by the dye dissolved in the plastic coating. A fraction of the intensity of this fluorescence light travels back along the fiber to the fiber segment 15A and photodetector 17. The

fluorescence light arriving at this photodetector has the same time-domain frequency f as that of the interrogating light, but has a phase shift relative to it, the magnitude of which depends on the fiber distance from point P to the electro-optical unit. Photodetector 17 receives, simultaneously, fluorescence light from other points along the fiber, with a phase shift different for each location. The phase angle $\Delta\theta$ (relative to the interrogating light) of the fluorescence light generated at any distance L' from the electro-optical unit is given approximately by the relation

$\Delta\theta = 360(2L'.f.n.c^{-1})$ degrees (15)

where n is the index of refraction of the glass, and

c is the velocity of light in a vacuum.

Now, one can apply a phase shift, by means of phase shifter PS, to the photo-electric signals produced by the group of fluorescence signals originating throughout the whole fiber length, so that the fluorescence originating at one location, (and only one location) produces a component of the photo-electric signal which is exactly in phase with the signal generated at photodetector 16. Now, if one varies the phase shift, for instance in the manner of a saw tooth ramp, one is effectively varying the location along the fiber where the generated fluorescence produces a photoelectric signal in phase with with the signal from photodetector 16. This component can be separated from the rest of the group of photoelectric signals by means of a lock-in amplifier controlled by the photoelectric signal from photodetector 16. By recording the output of the lock-in amplifier as a function of the applied phase shift one can, therefore, measure the magnitude of the forces acting on the fiber as a function of the fiber distance from the electro-optical unit.

Readers familiar with RADAR-ranging techniques may recognize the above method as an adaptation of said techniques to the optical fiber system of this invention.

The method is not restricted to fluorescent systems. Any system which produces distributed positive signals can be operated according to this phase shift method, including for example the force-sensing fiber shown schematically in FIG. 8, wherein the force signals carried by the region 3A are separated from the core light in the time domain.

6.0 DISTRIBUTED SENSING WITH RARE EARTH-DOPED GLASS FIBERS

The distributed sensors described hereinbefore using plastic-soluble fluorescent dyes should be adequate for most applications where the sensor is not subjected for extended periods to temperatures in excess of 150 degrees Celsius. If higher thermal stabilities are required, then an all-inorganic sensing fiber would be desirable. One perceived drawback of inorganic glasses is that none are known which combine a high luminescence quantum efficiency with the submicrosecond luminescence decay times conventionally required with OTDR systems. One object of this invention is to provide a method and its associated devices for performing distributed sensing with glass fibers doped with rare earth ions, with fiber length resolutions of a few meters or less despite decay times of their spontaneous luminescence longer than 10^{-4} seconds. The method is illustrated in this section with trivalent neodymium [Nd(III)] as an example, but other glass dopants capable of stimulated emission should also be useful according to the teachings of this section.

Nd(III)-doped glass has a high luminescence quantum efficiency, optical absorption bands in the 800-900 nanometer (nm) region (for which powerful laser diodes and LEDs are readily available), and luminescence bands from about 900 to 1330 nm. Additionally, it has an important property which compensates for its long luminescence decay time, namely the ability to generate stimulated emission from its excited $^4F_{3/2}$ level. If the optical excitation of Nd(III) is so intense that the occupancy number of this excited level exceeds the occupancy number of the lower level $^4I_{11/2}$ by a number ΔN (a condition known as population inversion), then light propagating through the system with a wavelength λ_l equal to a laser wavelength λ_L of Nd(III) and an intensity I_o will be amplified to an intensity $(I_o + \Delta I)$, the magnitude of $(\Delta I/I_o)$ being determined at least in part by ΔN. If the population inversion is achieved in a time of 10^{-7} seconds or shorter, then ΔI will reach a peak in a comparable period, regardless of the decay time of the spontaneous luminescence of Nd(III). The short response time permits the use of such a system for distance determination with an OTDR. The amplification process is illustrated by the model of FIG. 11. A 'pump' pulse of wavelength λ_s within an optical absorption band of Nd(III) generates the population inversion, which amplifies light of wavelength λ_L by stimulated emission. In this invention, the absorbed intensity of the pump pulse is determined by the value of the measurand (force or temperature). The use of fibers with cores of very small diameter (less than 10 micrometers) permits the production of the high excitation densities needed for pupulation inversion with relatively low power laser sources, even when the laser power has to be shared by numerous multiplexed sensing points. Examples follow.

6.1 A Distributed Temperature Sensor using a Nd(III)-doped Glass fiber.

A preferred embodiment is illustrated in FIG. 12. The 'pump' light source 10A is a pulsed laser emitting a beam of wavelength λ_v outside the range of wavelengths which can be amplified by an inverted population of Nd(III) ions, and which is selectively absorbed by Nd(III) ions occupying a thermally excited level with an energy E_v above the ground Nd(III) level. For measuring temperatures above about -100° C λ_v can be selected between about 920 and 980 nm, corresponding to E_v values between about 430 and 1030 cm^{-1}, depending on the composition of the base glass in which the Nd(III) ions are dissolved. The long sensing fiber 13C has a core made of Nd(III)-doped glass, with a diameter preferably not greater than 10 micrometers and a dopant concentration such that the optical density of the fiber at ordinary temperatures, over its whole length and at the wavelength of the interrogating (pump) light pulses, is between 0.1 and 0.3 (corresponding to attenuations between 1.0 and 3.0 dB), the fiber length chosen according to the particular application. The pump pulses, with a duration preselected according to the spatial resolution desired, and an energy preselected to generate population inversions along the fiber at temperatures within the range of interest, are launched into the fiber core, wherein a fraction α_v of their intensity is selectively absorbed by Nd(III) ions occupying the thermally excited level of energy E_v. The value of α_v is a function of temperature approximately according to equation (3) in section 2.1 above. The higher the value of α_v, the greater the population inversion at the Nd(III) level $^4F_{3/2}$ relative to level $^4I_{11/12}$, and the greater the amplification of the intensity of the counterpropagating light of the laser wavelength λ_L (FIG. 11).

For measuring temperature distributions one injects into the same fiber core, but at the distal end, a continuous, moderate power (~25 mW) laser beam from a Nd(III)-doped glass fiber laser 25 pumped by a laser diode 26. Fiber laser 25 has the same base glass composition as the long sensing fiber (except for a higher dopant concentration), so that its laser wavelength (near 1.08 micrometers) is essentially the same as that of the sensing fiber 13C. The latter is 'pumped' with a power high enough to produce stimulated emission. Now, as the temperature of any segment along the sensing fiber increases from an initial value of T_1 to T_2, the number of Nd(III) ions excited to the $^4F_{3/2}$ level increases from N_1 to N_2 approximately according to the relation

$N_2/N_1 = \exp[E_v(T_2-T_1)/kT_1T_2)]$

when excited with pump pulses from laser 10A. When the number of Nd(III) ions in the excited $^4F_{3/2}$ level exceeds the number in the lower level $^4I_{11/2}$ (FIG. 11), the counterpropagating light from the fiber laser 25 is amplified. The intensity gained, ΔI, will produce a pulsed signal arriving at the photodetector 16 in a time, relative to the time of launching of the excitation (pump) laser pulse, which is a known function of the location along the fiber from which the amplified pulse originated, and an intensity which defines the temperature of the fiber segment segment. In order to correct the signal for any fluctuations of the intensity of the interrogating light pulses, one can monitor the intensity of the Rayleigh-backscattered light from the same fiber segment with photodetector 17. Both photodetectors 16 and 17 are made spectrally selective to the amplified laser light and the Rayleigh-backscattered light, respectively, by means of narrow bandpass optical filters.

At temperatures lower than about -100° C one has to reduce the value of E_v. This is done simply by decreasing the wavelength of the interrogating (pump) light. It is preferable to use wavelengths which excite the $^4F_{5/2}$ level rather than the $^4F_{3/2}$ level, as this will avoid the use of excitation wavelengths which could be amplified in the same direction as that of the interrogating light pulses (which would effectively compete with the amplification of the counterpropagating light of wavelength λ_L). Depending on the temperature range being measured, one may select an interrogating light wavelength between about 810 and 840 nm. Instead of short excitation pulses, one may use AC-modulated AlGaAs laser light, and measure temperature as a function of fiber distance to the electro-optical unit by the phase angle division multiplexing method disclosed in section 5.0, with the added feature of the counterpropagating C.W. laser beam from the light source 25 in FIG. 12.

An important advantage of the use of light amplification in the submicrosecond time domain is that thermal quenching should not operate to a major extent even at temperatures of about 250° C (and maybe even higher), provided that the quenching is due mainly to the shortening of the spontaneous luminescence decay time.

6.2 The Measurement of Both Force and Temperature Distributions on a Single Optical Fiber Probe.

An optical fiber having two light-guiding regions of different optical path length and a luminescence dopant in one of these regions can be used as a probe for measuring both distributed forces and distributed

temperatures according to the teachings of this invention. An example of a preferred embodiment of a device for measuring these distributed parameters is shown schematically in FIG. 13. The fiber 13D differs from the fiber shown in FIG. 8a only in that the glass core is doped with Nd^{3+} ions in a concentration sufficient to sustain a population inversion sufficiently high to produce amplification of a probing light beam of wavelength near 1.06 micrometers. Temperature measurement with this fiber is based on the principles set forth in sections 2.1 and 6.1 above. The light source 10A launches into one end of fiber 13D interrogating light pulses of pre-selected wavelength λ_v between about 920 and 100 nm, depending on the temperature range being measured, and with an energy sufficient to generate a temperature-dependent population inversion of the $^4F_{3/2}$ level of Nd^{3+}. At the other fiber end, a CW neodymium glass fiber laser 26 launches a CW probing laser beam of a wavelength of about 1.06 micrometers. As this probing light beam traverses a fiber segment containing a temperature-dependent population inversion, it will be pulse-amplified at that point. The time of arrival of the amplified light pulses at photodetector 16 identifies the location along the fiber where the pulse amplification took place, and the magnitude of the gain will be an indicator of the temperature of the segment.

Force distributions are measured according to the method described in section 3.2 above. The light source 10 launches into the core of optical fiber 13D at the end opposite to the one on which the interrogating light pulses of wavelength λ_v were launched, a train of interrogating light pulses of a wavelength λ at which the Nd^{3+} ions are transparent. At any point along the fiber where a force is acting, a fraction α of the intensity of each pulse is deflected into the fiber cladding, which has an optical path length substantially longer than that of the core. The pulses of deflected light arrive at photodetector 16A after an interval Δt following the arrival of the undeflected interrogating light pulses, the value of Δt being determined approximately by equation (12) above, which defines the position along the fiber where the force was acting. The intensity of the deflected pulses is an indicator of the magnitude of the force. Ratiometric operation is achieved by dividing the electrical signals generated at photodetector 16A by those of photodetector 17 generated by the rayleigh backscatterd light from the smae point where the force was acting.

6.3. The Sensing of Distributed Forces and Temperatures with a Single Twin-Core Fiber.

The principles of force sensing of this invention can be readily extended to optical fibers containing two (or more) cores within a common cladding, said cores being within such a configuration that a stress or other force on the fiber at any point causes a fraction α_s of the intensity of the interrogating light launched into one core to be coupled into the other core(s), where it is converted into luminescence light. FIG. 14 illustrates a preferred embodiment based on a two-core fiber. The fiber 13E consists of a clear glass core C1, a second core C2 made of glass doped with Nd(III), a first cladding 2A common to and around said two cores, and a second cladding 4A around the first cladding. Core C2 has preferably an index of refraction higher than that of core C1. Cladding 2A has an index of refraction slightly lower than that of core C1, and cladding 4A has an index of refraction substantially lower than that of 2A. The diameters of the two cores are preferably smaller than 10 micrometers. Force distributions are probed by launching interrogating light pulses of wavelength λ_s into core C1. A fraction α_s of the intensity of this interrogating light is ejected from the core under the action of a force at any point, and is absorbed in core C2, where it produces a population inversion as described hereinbefore, and pulse amplification of counterpropagating light of wavelength λ_f equal to or near 1.0 micrometers, the magnitude of which is made a known function of the magnitude of the population inversion and, hence, of the magnitude of the force. and the time of arrival of which to the measuring photodetector indicates the location along the fib where the force was acting. The wavelength λ_s can be, for instance, near 800 nm. Temperature distributions are probed by launching into core C2 interrogating light pulses of wavelength λ_v, for example 946 nm, and proceeding as already described in section 6.1.

Instead of a luminescent glass, core C2 could be made of a glass having a relatively high Raman scattering coefficient. A suitable Raman wavelength is then used for the counterpropagating light injected at the distal end into core C2.

Although FIG. 14 shows a circular cross section for the cladding surrounding the two cores, other cross sections may also be used, for instance an elliptical one.

Although the illustrated embodiments of devices based on fibers containing luminescent glass use Nd-(III) as a dopant, other trivalent rare earths capable of stimulated emission can be used as dopants for the practice of this invention, including ytterbium and erbium. Erbium is particularly useful in that silica-based glass doped with it can be excited and is capable of stimulated emission in the second spectral window of

optical fibers (from about 1.2 to 1.6 micrometers), where optical attenuation is particularly low over long fiber lengths.

The measurement of forces and/or temperatures with sensing fibers doped with luminescent rare earth ions can also be effected with the phase angle division multiplexing technique disclosed in section 5.0 above using, instead of pulsed interrogating light, AC-modulated interrogating light and a device like the one illustrated in FIG. 10 additionally comprising a source of counterpropagating light of wavelength λ_L injected into the sensing fiber at the end opposite to the launch end of the AC-modulated interrogating light.

6.4 An Alternate Method for Measuring Distributed Temperatures with a Single Unbroken Optical Fiber Probe

Another method for measuring distributed temperatures according to this invention uses a temperature-dependent light distribution between two light-guiding regions of an optical fiber. One of the preferred embodiments uses a fiber shown schematically in FIG. 15. It comprises a glass core A (the first light-guiding region) with an index of refraction n_1, a first cladding B (the second light-guiding region), having a temperature-dependent index of refraction n_2 lower than n_1, and a second cladding C around the first cladding, having an index of refraction n_3 lower than n_2. The launch end of the fiber is aluminized on the face of the two claddings, so that the interrogating light can be launched only through core A. The interrogating light is launched as a recurrent train of short pulses with a duration of the order of a few nanoseconds (ns) or shorter, depending on the spatial resolution desired (approximately 10 ns per meter), over an acceptance angle θ for meridional rays necessary to fill the numerical aperture $(NA)_2$ defined as

$(NA)_2 = (n_2^2 - n_3^2)^{\frac{1}{2}}$

In other words, the interrogating light fills both light-guiding regions A and B. The value of n_2 decreases in a known manner with an increase in temperature, at a much greater rate than the decrease in the value of n_1, and the intensity distribution of the interrogating light pulses between regions A and B will be determined by the relative values of the squares of $(NA)_2$ and the numerical aperture $(NA)_1$ of core A, defined as

$(NA)_1 = (n_1^2 - n_2^2)^{\frac{1}{2}}$

The value of $(NA)_2$ can be kept approximately constant over the working temperature range by making cladding C out of a material such that its index of refraction n_3 has essentially the same temperature coefficient as the index of refraction n_2 of cladding B.

Now, the intensity of the light Rayleigh-backscattered from the core A at any resolvable segment of the fiber, corrected for the intrinsic light attenuation of the fiber per unit length, will be a known function of the temperature of the segment. In contrast to prior art methods of temperature measurement using a temperature-dependent index of refraction, cross-talk between different sensing points is minimized by virtue of the fact that light rays deflected out of core A through a temperature change are not 'thrown away' as in the prior art, but captured and returned to the region comprising core A and first cladding B, thus restoring a temperature-dependent light distribution at every segment of the fiber.

Since the cladding faces of the fiber are aluminized (or otherwise made opaque), and the diameter of cladding B can be made much larger than that of core A, the intensity of the Rayleigh-backscattered light collected at the core launch end from any resolvable segment of the fiber will be proportional to the intensity of the interrogating light propagating within the core at that segment, determined by the value of $(NA)_1$ and, hence, by the temperature-dependent value of n_2. Any contribution from cladding B to the collected Rayleigh-backscattered light can be further minimized by using a small collection angle consistent with the needed signal intensity.

The sensitivity and performance of the proposed distributed sensor may be anticipated from the following assumed conditions:

The sensing fiber comprises a core A made of silica glass with an index of refraction n_1 of 1.45800, an elastomeric silicone cladding B with an index of refraction n_2 of 1.45030 at the temperature of 300 K, and a second silicone cladding C with an index of refraction n_3 at 300 K of 1.41900. Both n_2 and n_3 have a temperature coefficient of 2×10^{-4} per kelvin. Then a change of 1 kelvin from 300 K to 301 K will increase the value of $(NA)_1^2$, and hence of the intensity of the Rayleigh-backscattered light, by 2.6 percent, a rather large change compared to prior art fiberoptic temperature-sensing systems.

The spatial resolution of the system depends on the risetime and/or duration of the interrogating light pulses. Using an optical time domain reflectometer (OTDR) and light pulses with a duration of 100 picoseconds (ps), for example, one could obtain a spatial resolution of the order of 10 cm, limited by time dispersion effects in the fiber.

Another embodiment of these sensors uses fibers wherein both claddings, as well as the core, are made of glass, with the first cladding having an index of refraction with a temperature coefficient different from that of the core. While glass has lower temperature coefficients for its index of refraction than plastics, the change may be sufficient for a number of applications, especially at high temperatures at which a plastic cladding would degrade.

7.0 MISCELLANEOUS APPLICATIONS OF THE INVENTION

7.1 Optical Tactile Sensors for Robots.

The teachings of this invention lend themselves to the construction of new useful devices. The same principles described above for the measurement of both forces and temperatures with a single sensor can be used to construct a two-dimensional tactile sensor for robots, also sensitive to both forces and temperature. The sensor can be understood with reference to Figure 16. It consists of a clear elastomeric "sandwich" pad comprising three layers 31, 32, and 33. The inner layer 31 has an index of refraction n_1, and is bounded by the upper layer 32 and the lower layer 33, having indices of refraction n_2 and n_3, respectively, such that $n_1>n_2>n_3$. In one embodiment layer 31 has a thickness of about 200 micrometers, while each of the layers 32 and 33 have a thickness of about 100 micrometers. Layer 32 has dissolved therein a fluorescent dye characterized by a high fluorescence quantum efficiency and an optical absorption coefficient which is a sensitive function of temperature when illuminated with light of wavelength λ_v. When illuminated with light of a wavelength λ_s shorter than λ_v, the absorption coefficient of the dye is independent of temperature within the temperature range of operation of the device.

The fluorescent layer has an electrically conductive film 34 applied to it, having a resistivity such that a relatively low current passed through it will heat layer 32 to a a temperature of about 40 °C, or to any other chosen temperature.

The outer faces of layers 32 and 33 are coated with strips 35 of black paint as shown in the top view of Figure 13, with a width at least ten times greater than the thickness of layer 31.

The whole pad is in contact, through layer 33, with a two-dimensional silicon imaging array 36, having a light-sensitive surface covered with a dielectric optical filter 37, which is selectively transparent to the fluorescence wavelengths of the dissolved dye, and blocks the wavelength λ_s of the illuminating light source.

The sensor pad works as follows:

Light of wavelength λ_s is injected into layer 32, uniformly from one or, preferably, two or more square sides. The injected light has an angular distribution such as to overfill the numerical aperture (NA) of layer 31 defined by the relation

$$(NA) = (n_1^2 - n_2^2)^{\frac{1}{2}}$$

The light rays having angles smaller than the critical angle θ_c for total internal reflection enter layer 32 and are 'stripped' by the black paint strips. The light reaching the clear inner square of the pad is propagated inside layer 31 by total internal reflection at the boundaries between layer 31 and layers 32 and 33. Any pressure at any localized point 38 on the pad causes a deformation which forces a fraction of the intensity of the light propagation through layer 31 into layer 32, thus causing a fluorescence emission from the dissolved dye, which is detected by the detector(s) in the imaging array located just below the point 38. The intensity of the generated fluorescence is determined by the magnitude of the deformation and, hence, by the magnitude of the pressure at that point. If pressure is applied at a plurality of points within the clear area of the pad (that is, within the area bordered by the black strips) the silicon sensor array will generate a two-dimensional map of the forces acting on the pad.

After a video frame is obtained, the process is repeated, except that the light injected into layer 31 now has the wavelength λ_v. This wavelength will produce a fluorescence intensity from the dye which is determined by the temperature of layer 32 as well as by the pressure applied at point 38. The ratio of the fluorescence intensities produced by the two illuminating wavelengths defines the temperature at point 38, while the fluorescence intensity produced by the illumination wavelength λ_s defines the magnitude of the pressure or force.

7.2 Fiberoptic Keyboards

The British journal Sensor Review (April 1984, pp 70-72) discusses the need for electrically passive fiberoptic keyboards in some environments where electronic keboards may be unsuitable, for example in underwater applications, in flammable atmospheres, or in electrically noisy environments, and describes a complicated experimental fiberoptic keyboard. The teachings of this invention for the trapping and modification of light deflected out of the core of an optical fiber under an acting force can be used to construct improved, simpler keyboards. In contrast to the device described in said issue of Sensor Review, which require $2.N^{\frac{1}{2}}$ sequentially pulsed light sources for a number N of keys, the fiberoptic keyboards of this invention require not more than one light source. Furthermore, this single light source can be shared by numerous fiberoptic keyboards operated simultaneously.

An example of a fiberoptic keyboard using the principles of this invention uses two identical optical fibers, each comprising, a) a clear core having an index of refraction n_1; b) a clear cladding around said core, having an index of refraction n_2 lower than n_1 and a thickness of a few micrometers; c) a second cladding having an index of refraction n_3 not lower than n_2 and a diameter preferably greater than twice the core diameter and having also a wavelength-selective light absorber dissolved therein; and d) an outer cladding with an index of refraction n_4 lower than n_2.

A general representation of the optical transmission spectrum of a suitable light absorber is shown in FIG. 17, which also includes a typical output spectrum of a C.W. light-emitting diode (LED) used for operating the keyboard. In the keyboard system, a length L of each fiber is used such that the total optical density to light of wavelength λ1 propagating along the light-guiding region including the light-absorbing second cladding is about 1.3, corresponding to a transmitted light intensity P of about 5 percent of the incident light intensity P_o, according to the relation

$\log(P/P_o) = -\alpha L$

where α is the absorption coefficient of the light-absorbing second cladding per unit length, the product αL being the full-length optical density of the fiber.

FIG. 17A is a schematic representation of the operating keyboard. Two fibers, F1 and F2, are laid out as shown under an 8x8 matrix of keys, F1 passing under all rows of keys and F2 passing under all columns of keys, the two fibers intersecting under each key as shown in the area of detail under the matrix. Between each contiguos rows and columns of keys there is a fiber segment S of length z, at least 10 times longer then the fiber segment under each row or column of keys. When a key is depressed, at least an appreciable fraction of the intensity of the interrogating light launched into the core of each fiber by the LED is deflected into the light-absorbing second cladding. The deflected light propagates within the light-guiding region including said second cladding along the fiber length to the photodetection station PS, and the spectral component of wavelength λ1 is partially absorbed. The transmitted light intensity P_i of wavelength λ1 is given by the relation

$\log(P_i/P_o) = \alpha L(1 - N'z' - x)$

where z' is equal to z plus the length of fiber under a row or column of keys,
N' is the number of rows or columns (depending on whether the fiber is F1 or F2, respectively) preceding the row or column of the depressed key; and
x is the length of fiber under the preceding keys of the same row or column of the depressed key.

Since z' is more than 10 times greater than x, the value of x, determined by the number of preceding keys in the same row or column, won't affect appreciably the measured value of P_o. Additionally, light of wavelength λ2 is not absorbed appreciably by the light-absorbing material. Therefore, the ratio of the light intensities of wavelengths λ1 and λ2 transmitted by each fiber will be a unique function of the location of the depressed key. The light outputs from each fiber are fed to two photodetector pairs, PD1-PD2 and PD1'-PD2', the digits 1 and 2 representing that the photodetectors are selectively sensitive to wavelengths λ1 and λ2, respectively.

For a full-length optical density of 1.30, the light intensities of wavelength λ1 transmitted by each fiber for keys depressed at two contiguous rows or columns varies by about 30 percent for an 8x8 matrix of keys from one row or column to the next, and the percentage of variation increases as the full-length optical density increases. Therefore, the set of readings from the two sets of photodetectors, for each depressed key, will unambiguously identify the key.

The reading can be made independent of any variation of the fraction of the interrogating light intensity deflected into the absorbing cladding, by directing only the deflected light to the photodetectors. This can be achieved simply by covering the output tip of the fiber core by a black absorber, or by other means which would be apparent to workers with at least average competence in the art to which this invention pertains.

In a variant of the above method, the light-absorbing material in the second cladding is luminescent, and light of the shorter wavelengths within the luminescence spectral output is partially reabsorbed, the

extent of the reabsorption varying as a function of the distance from the point under the depressed key to the distal end of the fiber, the luminescence emitted at longer wavelengths being only minimally absorbed. In this case one identifies the depressed key by the ratio of the intensities of the lights emitted at the two wavelength regions. One specific example of such a luminescent system is Nd(III)-doped glass, the luminescence spectrum of which comprises a band at about 890 nm, and another strong band at about 1060 nm (in addition to at least another band at longer wavelengths). The luminescence light within the 890 nm band is partially reabsorbed, while the band at about 1060 nm is only minimally attenuated, and can be used as a reference.

Another kind of keyboard, suitable for multiplexing, is illustrated in FIG. 17B. A light source 10, preferably an LED or a laser diode, is driven from power supply 9 to produce a recurrent train of light pulses with a duration preferably not greater than about 20 nanoseconds, and a repetition rate of 10^4 pulses per second. At the keyboard the optical fiber 13B is laid out as shown, with intersecting horizontal and vertical segments, and with a depressable key at each inersection. Between each contiguous rows or columns of keys traversed by fiber 13B there is a fiber segment of length L of about 2.0 meters, designed to delay the time of arrival of the interrogating light pulses at any row or column by about 10 nanoseconds after the preceding row or column. At any key position, the set of fiber distances from the point of intersection to the electrooptical unit EOU is unique for that key. As the key is depressed, a small (but easily measurable) fraction of the intensity of the interrogating light propagating through the fiber core is forced into the fiber cladding and the interface between this cladding and the fluorescent coating 4′. The fluorescence light pulses generated at the evanescent wave layer of the coating arrive at the photodetector 23 at two specific times (relative to the time of injection into the fiber of the interrogating light pulses) which uniquely identify the key. The power supply 9 provides the reference timing pulse which triggers the time sweep of the timer TR. The time interval between the fluorescence pulses from contiguous rows or columns of keys is approximately 20 nanoseconds. In the illustrated example, the total length of optical fiber needed for 49 keys is 28 meters. In general, the total fiber length L needed for any number N of keys is given by

$$L = (tc/n).N^{\frac{1}{2}}$$

where c is the velocity of light in a vacuum;

t is the needed time resolution; and

n is the index of refraction of the glass in the fiber. (Although the indices of refraction of the core glass and the cladding glass are slightly different, they are sufficiently close to 1.50 to use this value in most design calculations).

The electro-optical unit described above can be used, without major modifications, to interrogate and read out a multiplicity of keyboards in a series array on a single fiber, or in parallel on a plurality of fibers.

The technique described above for the for the time-division-multiplexed keyboard can be used with any fiber in which light deflected from the core into another light-guiding region can be separated in the time domain from the interrogating light. The fiber 13A subject of FIG. 8 is an example of an optical fiber also suitable for use in fiberoptic keyboards. In this case the light deflected under the action of a depressed key is separated in the transmission mode as discussed in section 3.2

8.3. The Multiplexing of Sensors on a Single Unbroken Optical Fiber.

Distributed force sensors can be used for multiplexing sensors for any physical variable which can be converted into a mechanical force. The distributed fiber sensors of this invention can receive inputs from any such sensor at any desired location, and transform those inputs into luminescence signals when the optical fiber is interrogated by a suitable light source in a device like an optical time domain reflectometer (OTDR). As explain hereinbefore, the intensities and the time characteristics of these luminescence signals define both the location along the fiber where the sensor is located and the value of the measurand. A preferred type of sensor to be coupled to the distributed sensing fibers of this invention is the well-known microbend sensor. Examples of microbend sensors which can be multiplexed on a sensing fiber of this invention are:

(a) microbenders mechanically coupled to a displacement-type sensor, for instance the diaphragm of a pressure-sensing transducer. Thus the sensor can be entirely electrically-passive; and

(b) electrically-driven microbenders, in which case only the signal transmission through the fiber will be electrically passive.

A preferred way of coupling sensor information into an optical fiber according to this invention is to convert the sensor output into an oscillatory force applied to the fiber, the oscillatory frequency being a known function of the value of the parameter being measured. A frequency signal is transmitted through an

optical fiber with less degradation than an intensity signal.

8.0. Non-Imaging Optical Concentration Techniques Relating to this Invention.

Unlike the embodiments of this invention based on the use of fluorescent dyes, the embodiments based on glasses doped with luminescent rare earth ions must use high excitation densities in order to achieve stimulated emission and probe light amplification in distributed sensing systems. The way to achieve these high excitation densities with excitation sources of low or moderate power (not more than a few hundred milliwatts) is to confine the excitation energy into an active wave-guiding region of the sensing fiber having a very small cross section. The emitting areas of many otherwise convenient light sources are often much larger than such needed small cross-sections. Commercial laser diode arrays have output powers from 790 to 870 nm of the order of 1 Watt C.W., originating from a rectangular source about 200 micrometers wide and about 1 micrometer high. One could clearly not image more than a few percent of this power into a fiber core with a diameter of a few micrometers. If, however, the core contains a luminescent material which efficiently absorbs the output of said diode laser array, one could concentrate at least a large fraction of the energy emitted by the array into said core, without violating the second law of thermodynamics, by means other than the imaging of the light source into the core launch end. One way is to enclose the luminescent core within a clear first cladding of conventional circular cross-section, into which the light source is imaged. A far more efficient arrangement is disclosed herein, using as an example a temperature-sensing optical fiber based on Nd(III)-doped glass. The principle is shown in the preferred embodiment illustrated in FIG. 18. It uses a fiber 13F with a light-guiding region A having an index of refraction n_a and a near rectangular cross-section, with its height about equal to or not much higher than the diameter of the cylindrical Nd(III)-doped core B, of not more than about 10 micrometers (µm), and a width not much greater than, and preferably equal to, the active width of the diode laser array (~200µm). The index of refraction n_b of the doped core is higher than n_a. Around region A there is a cladding C with an index of refraction n_c lower than n_a. Light from the laser diode array is launched into region A wherein it propagates and, at each pass along the width of the near rectangular cross-section, it passes through the doped core, a small fraction of its intensity is absorbed by the Nd(III) in the core, until essentially its whole intensity is absorbed in the core. The optical energy that can thus be coupled into the core can be many times greater than that which can be launched into the core end. Furthermore, the near rectangular cladding A of FIG. 18 affords more efficient pumping per unit fiber length than an arrangement using a conventional cylindrical cladding of diameter equal to the active width of the diode laser array. In the latter case, if the doped core is at the center, then the so-called 'skew' rays, which would outnumber the so-called 'meridional' rays, would not enter the doped core and would not contribute to the pumping. And if the doped core is placed near the edge of the cylindrical cladding in order to capture the skew rays, then the excitation yield per unit fiber length would be many times lower than in the case of the near rectangular cladding A, as the cross-sectional area relative to the cross-sectional area of the doped core is much larger.

A distributed force-sensing fiber using the same optical concentration principles must be adapted to meet the requirement of a minimal luminescence background per resolvable fiber length in the absence of an external force (or internal strain). Such a fiber is illustrated in FIG. 19. The waveguiding region A′ into which the interrogating light is launched has a cross section about an order of magnitude greater than that of the Nd-doped core B. Between core B and region A′ there is a cladding C having an index of refraction lower than those of core B and region A′. Core B hs an index of refraction not lower than that of region A′. Around region A′ there is a second cladding D having an index of refraction lower than that of the first cladding C. At any point along the fiber where a force is acting, a fraction α_s of the intensity of the interrogating light launched into the light-guiding region A′ is ejected into cladding C and core B, where it produces a population inversion of the Nd(III) ions. The Nd(III) concentration in core B can be pre-selected so as to cause total absorption of the force-coupled interrogating light over the resolvable fiber length (for instance 1 meter). The wavelength λ_s of the interrogating light can also be pre-selected for optimum absorption. The strongest absorption band of Nd(III) in the near infrared region peaks at or near 805 nm, generated by efficient, commercially available diode lasers, including diode laser arrays. One could also use interrogating light pulses with powers of the order of hundreds of watts or more, and durations of the order of 10^{-7} seconds or less, without generating stimulated Brillouin scattering or stimulated raman scattering that would occur if the same powers were launched directly into the fiber core.

Distributed force sensing with the above fiber can be carried out according to the phase angle division multiplexing technique discussed in section 5.0 above, using a counterpropagating moderate power (~25mW) continuous laser beam to probe the population inversion in the fiber produced by the action of the

forces to be measured. In order for the method to be applicable, the amplification of the probing counterpropagating light must occur at the same time domain frequency as that of the light modulation at the source. This requires that the smallest forces to be measured cause a population inversion in each of the sensing points along the fiber. If there are, for instance, 50 for more sensing points, it may be necessary to couple into core B an optical power of the order of 100 milliwatts or more of the AC-modulated light from the 'pump' laser (or array). The concentration technique disclosed herein facilitates this task.

This concentration technique is also valuable for coupling into an optical fiber an optical power high enough to cause undesirable non-linear effects or damage if focused directly into the launch end of the fiber core.

The optical concentration method of FIG. 18 can also be used for 'pumping' a fiber laser or amplifier with a light source of larger cross section than that of the emissive region of the fiber laser or amplifier.

9.0. Applications of this Invention to Fiber Optic Communications.

The provision of a luminescent waveguiding region to an optical fiber, in addition to the standard glass core and glass cladding of communication fibers, and without affecting the light propagation properties of these standard waveguiding regions, allows a plurality of new communications-related uses of the fiber, besides its use as a distributed sensing probe. Two of such uses are outlined below:

Improved Diagnostics of Fiber Optic Networks.

In its simplest embodiment as a distributed sensing probe, the force-sensing fiber of this invention is essentially a standard communications fiber with a standard core, a standard cladding, and a plastic coating around the cladding which, except for a few parts per million of a fluorescent dye dissolved in it, would be essentially the same as some of low index polymers presently used for the protective coating of optical fibers. Yet it is that minute concentration of the dye which enables the fiber to produce diagnostic signals from lossy points along the fiber which are orders of magnitude stronger than those from the decrease of the intensity of the Rayleigh-backscattered signals conventionally measured with OTDR diagnostic instruments, but without affecting the communication signals propagating along the fiber core. The force-sensing fiber of this invention could, therefore, be used as a communications fiber in local area networks, and its force-sensing characteristics would be a built-in diagnostic feature which would greatly extend the capability of optical time domain reflectometry. This communications fiber could be used, additionally, for distributed sensing, and the sensor information would be transmitted through the same fiber without interfering at all with its usual communication functions.

The Non-invasive Coupling of Information to the Fiber from the Side at Any Point.

The force-sensing fibers of this invention allow the non-invasive coupling of information into the fiber from the side at any point. The information can be coupled in digital form by any sequence and/or timing of 'force bits' applied by means of, for example, a piezoelectric transducer, when a train of short interrogating light pulses are propagating along the fiber core. The coupled information, converted either to fluorescence light pulses if the fiber has a fluorescent cladding, or to time-resolved light pulses if the fiber is like the one described in section 3.2 supra and FIG. 8, will then propagate to at least one fiber end time-and/or wavelength-separated from the interrogating light. Information can also be coupled by direct optical excitation of the fluorescent cladding by an external light source.

10.0 A Medical Application: Laser Surgical and Photo-Irradiation Tips Which Are Also Temperature-Sensing Probes.

In recent years there has been a large increase in the use of high power lasers in medicine, for applications like surgery, hyperthermia, photodynamic therapy, and other laser irradiation techniques. In one type of application, laser energy conducted by an optical fiber or fiber bundle to a surgical tip heats up the tip to permit operations requiring controlled heating of the biological tissue being worked on. Unfortunately, there is no reliable means for measuring the temperature of the heated tip. Thermal measurements are

usually conducted by placing a temperature sensor at some distance from the tip, but this is not an adequate substitute for measuring the temperature at the tip itself.

The teachings of this invention permit one to make surgical tips which are also their own temperature probes and which, in addition, can function as light diffusers for medical photoirradiation purposes.

An example of a surgical tip/light diffuser according to this invention is illustrated in FIG. 20. It consists of a length of clad rod 80 of similar diameter to that of the optical fiber to which it is attached, and having dissolved therein a luminescent material with a luminescence spectrum suitable for the intended treatment, if used for photo-irradiation, at a concentration pre-determined to convert the desired fraction of the excitation light into luminescence light.

Used as a surgical tip, the rod, which may be terminated in a point as shown, is heated by absorption of laser radiation from sources like an excimer laser (ultraviolet), an AlGaAs laser array or a carbon dioxide laser. The laser radiation is delivered through an optical fiber 81, at a power and energy needed for heating the rod to the desired temperature range. Suitable based materials for the rod are sapphire and yttrium aluminium garnet, suitably doped with a luminescent material. A suitable dopant for yttrium aluminium garnet (YAG) is Nd^{3+}, the doped material being designated herein as Nd:YAG

The probe can be used as a temperature sensor (usually to measure the temperature at which it has been laser-heated) by the method disclosed in section 2.1, above. Nd:YAG, for example, can be interrogated with light of wavelength of 946 nm. Under this illumination, the probe absorbs a temperature-dependent fraction α_v of the interrogating light determined by equation (3), with E_v being approximately equal to 857 cm^{-1}. The luminescence intensity of the probe will follow aproximately equations (4) and (5).

The same probe can also be used as a light diffuser. The Nd:YAG probe can be excited through the fiber 81 by a high power AlGaAs laser diode array emitting at about 805 nm, within a strong absorption band of Nd:YAG. The absorption energy is converted into luminescence light which is emitted nearly isotropically from the probe, thus affording homogeneous illumination of the biological tissue surrounding the probe. Other luminescent dopants like Cr^{3+}, Er^{3+} or Ho^{3+} can be used for providing illumination at different wavelengths, depending on the dopant.

11.0 Sequential Multiplexing and Transmission of Signls from Electronic Sensors on a Continuous Length of Optical Fiber.

The systems described above for the measurement of distributed forces using as a sensing probe a continuous length of an optical fiber are all based on the use of at least two light-guiding regions in the optical fiber, wherein a fraction of the intensity of the pulsed or AC-modulated interrogating light launched into one region is deflected into the second region. Several types of such fibers have been described and illustrated with appropriate figures, where the two light-guiding regions are labelled differently for different fiber types. For the purposes of this application the light-guiding region into which the interrogating light is launched is designated herein as region A, regardless of the type of fiber, and the light-guiding region into which a fraction of the intensity of the interrogating light is deflected is designated as region B. In all of the above-described embodiments the light deflected into region B at any point along the fiber is processed within region B into a light separable from the interrogating light and from light deflected at any other point by another force acting simultaneously on the fiber. In the case of the optical fiber described in section 3.2, the lights deflected into region B at different points are separated in the time domain in the transmission mode, by causing them to arrive at the distal fiber end at different resolvable times. This fiber, like the ones in which luminescence conversion occurs in region B, can be used for multiplexing the signals coupled simultaneously into the fiber by numerous sensors or other devices. In many industrial applications the signals may be coupled into the fiber sequentially, rather than simultaneously, so one can use a simpler force-sensing fiber, and the system must comprise means for instructing the sensors (or other devices) to couple their signal into the fiber in the proper sequence. Such a system is described below, with reference to FIG. 21.

Referring to FIG. 21, the fiber system comprises fibers F1 and F2 spliced together at point P′. Both fibers F1 and F2 comprise a glass core 1 with an index of refraction n_1 and a glass cladding 2 with an index of refraction n_2 lower than n_1. Fiber F1 has a transparent coating 3′ around cladding 2, having an index of refraction n_3 not lower than n_2. Fiber F2 has a transparent second cladding 4 around cladding 2, having an index of refraction n_4 lower than n_2. Sensors S_1, S_2, S_3 and others not shown are connected non-invasively to fiber F1 through their photodetectors P_1, P_2, P_3 and others. The non-invasive connection consists of a microbend on the fiber. The microbend deflects a fraction of the intensity of the interrogating light from light source LS out of the fiber core 1 into the cladding 2 of fiber F1. An index-matching transparent

thermoplastic adhesive couples the deflected light to the photodetector. The interrogating light is in the form of short light pulses superposed on a continuous DC or AC beam. Each light pulse instructs the sensor to 'write' its signal output (for instance the magnitude of a pressure) on fiber F2 after a pre-selected interval t and for a time $\Delta t'$. Each interval t is set so that a sensor 'writes' its information on fiber F2 after the preceding sensor has finished coupling its own information into the fiber. The 'writing' consists of, for example, a microbending force with a frequency which is a known function of the value of the measurand. The microbending force is produced by a piezoelectric transducer PZT mechanically connected to a fiber microbender M. The microbending force deflects a fraction of the intensity of the interrogating light out of the fiber core 1 into cladding 2, where it is trapped by total internal reflection from the second cladding 4 and transmitted to the photodetector PD. The optical interface between fiber F2 and photodetector PD can be so designed that only the cladding modes reach the photodetector, so as to eliminate or minimize the background noise from the core modes.

The sensors themselves are preferably, but not necessarily, silicon micromachined sensors requiring only small electrical powers to operate, typically of the order of tens of microwatts. Thus they can be powered by small batteries which, due to the low powers required, could give years of unattended service. Alternatively, the sensors could be powered remotely by light source LS.

The electronic system which instructs each sensor to couple its information to fiber F2 at a pre-set time is essentially a light-activated switch with a time delay for opening and closing, relative to the time of arrival of the light pulse at the photodetector. Such timed electronic switches are well known in the electronics field.

The system described with reference to FIG 21 is an example of a so-called "hybrid" system, comprising electrical sensors and fiberoptic transmission of the sensor signals. A well designed hybrid system combines the advantages of already proven electrical sensor technology with the immunity to electromagnetic interference of optical signal transmission.

One advantageous feature of the system illustrated in FIG 21 is the capability of inter-sensor or inter-device communications. Light source LS can transmit any information to any device connected to the fiber through its photodetector, including commands to perform any function for which the sensor or device is suited. If, for example, it is required that sensor S_1 transmit the value of the physical parameter it is monitoring to sensor S_3, then the microprocessor which processes the photosignals from photodetector PD will feed back the information from sensor S_1 to the power supply of the light source LS, and this information will be converted into a modulation of the light output of LS as it is transmitted in the code for sensor S_3. Thus any sensor or device in the multiplexed system can 'talk' to any other sensor or device.

The advantages of sequential reading of the outputs of all the sensors include the following:

1) All the sensors and/or other devices may share a relatively short length of conventional optical fiber (whether single mode or multimode) with no cross-talk problems;

2) The power requirements of the interrogating light source are are greatly reduced compared to the case if all the sensors had to transmit their information to the photodetector PD simultaneously; and

3) The electro-optical system, including the information-processing hardware, is greatly simplified, as the signal from one sensor only is received by the photodetection system at any one time.

Since certain changes may be made in the foregoing disclosure without departing from the scope of the invention herein involved, it is intended that all matter contained in the above description and depicted in the accompanying drawings be construed in an illustrative and not in a limiting sense.

Claims

1. An optical fiber adapted to sense physical forces at different points along its length, comprising at least a light-guiding region A into which interrogating light is launched and a second light-guiding region B, and characterized by deflecting under the action of a force at any point, when interrogated by pulsed or AC-modulated light within a pre-selected wavelength region and of pre-selected duration or frequency, a fraction α of the intensity of the interrogating light pulses being transmitted through region A into region B, said region B adapted to automatically process said deflected light and transmit it to as least one fiber end in a form which makes said deflected light resolvable from interrogating light transmitted through region A and from light deflected from region A to region B at other points along the fiber.

2. An optical fiber as claimed in claim 1 wherein said light-guiding region A is the fiber core, and said light-guiding region B is a cladding around said core and has a fluorescent material dissolved therein and adapted to automatically convert said deflected light into fluorescence light having wavelengths different and separable from the wavelength or wavelengths of the interrogating light.

3. An optical fiber as claimed in claim 1 wherein said light-guiding region A is a core having an index of refraction n_1 bounded by a first cladding having an index of refraction n_2 lower than n_1, the relative values of n_1 and n_2 being such that the value of $(n_1^2 - n_2^2)^{\frac{1}{2}}$ does not exceed 0.15, and said light-guiding region B is a second cladding around and in contact with said first cladding, having a graded index of refraction the highest value of which, n_3, is at least two percent higher than n_1, the higher value of n_3 adapted to cause said light deflected at each sensing point to arrive at the fiber distal end at different, resolvable times from the times of arrival of the undeflected interrogating light and from the times of arrival of the lights deflected from region A to region B at other sensing points along the fiber.

4. A force-sensing arrangement of the optical fiber claimed in claim 2 and additionally comprising:

a) means for generating and launching said pulsed or AC-modulated interrogating light into the fiber core at the launch end of said fiber;

b) means located at or near the launch end of the fiber for directing the fluorescence back-emitted from force-sensing points along the fiber to photodetection means for providing force measurements.

5. A force-sensing arrangement comprising the optical fiber claimed in claim 3 and additionally comprising:

a) means for generating and launching said pulsed or AC-modulated interrogating light into the fiber core at the launch end of said fiber; and

b) photodetector means for processing the light deflected at each sensing point and for providing force measurements.

6. A force-sensing arrangement as claimed in claim 5 and adapted to the non-invasive coupling of information into an optical fiber from the side at any point, the arrangement additionally comprising means to convert the information to be coupled into forces applied laterally to the fiber.

7. An optical fiber comprising:

a) a fiber core made of a luminescent material capable of stimulated emission and having an index of refraction desigmnated herein as n_1; said core designated herein as the fiber's first light-guiding region;

b) a second light-guiding region around said core, having an index of refraction n_2 not higher than n_1 and an elongated cross-section with a long dimension much greater than the diameter of the core, and a dimension, perpendicular to said long dimension, approximately equal to or not more than a few micrometers greater than the diameter of said core; and

c) a cladding around and in contact with said second light-guiding region, said cladding having an index of refraction n_3 lower than n_2.

8. An arrangement for pumping a fiber laser or optical fiber amplifier, comprising:

a) an optical fiber as claimed in claim 7; and

b) means for launching excitation light into said second light-guiding region, said light having wavelengths within an optical absorption band of said luminescent material.

9. A temperature measuring arrangement comprising:

a) an optical fiber comprising a core with an index of refraction n_1, a first cladding around said core having an index of refraction n_2 lower than n_1, the value of n_2 decreasing in a known manner with an increase in temperature at a greater rate than the decrease in the value of n_1, and a second cladding around said first cladding, having an index of refraction n_3 lower than n_2;

b) means for generating and launching interrogating light pulses of submicrosecond duration into the core and the first cladding at the launch end of said fiber; and

c) means located at or near the launch end of said fiber for directing light backscattered within the fiber core at temperature measurement points along the fiber to photodetector means, the intensity of said backscattered light at each measurement point being an indicatoe of the temperature at that point.

10. A force-sensing optical fiber, comprising:

(a) a clear core having an index of refraction n_1;

(b) a clear first cladding around and in contact with said core, having an index of refraction n_2 lower than n_1;

(c) a second cladding around and in contact with said first cladding, having an index of refraction n_3 not significantly lower than n_2 and characterized by a length-dependent partial absorption of interrogating light of suitable pre-selected wavelenghts λ_1 and a much weaker absorption of light of suitable pre-selected wavelengths λ_2; and

(d) a clear third cladding having an index of refraction n_4 substantially lower than n_2;

the fiber being so characterized that, when interrogating light composed of light of said wavelengths λ_1 and light of said wavelengths λ_2 is injected into one end (i.e. the injection end) of the fiber and propagated along said core towards the other end (the distal end), a bending force applied at any point along the fiber causes the deflection of a fraction α of the intensity of the interrogating light from the core to said first and said second claddings and the absorption of a fraction β of the intensity of the component of wavelengths λ_1 of

said deflected light, the magnitude of β being a known function of the location along the fiber where the force is acting, the relative intensities of the components of wavelengths λ_1 and λ_2 of the deflected light transmitted by said first and said second claddings to said other end being an indicator of the location along the fiber where the force is acting.

11. An optical keyboard system, comprising:

(a) an arrangement of depressable keys; and

(b) two optical fibers as claimed in claim 1, each of them being disposed under said arrangement of keys in such a manner that the two fibers intersect under each key of said arrangement, the depresssion of each key producing said bending forces at both fibers simultaneously.

12. An optical keyboard system as claimed in claim 2 and additionally comprising:

(a) means for generating and injecting interrogating light composed of said wavelengths λ_1 and λ_2 into the cores at the injection end of each of said two fibers; and

(b) photodetector means for measuring the relative intensities of the component of wavelengths λ_1 and the component of wavelengths λ_2 of the light deflected from the core to said first and second cladings of each of said two fibers and transmitted by said claddings to the fibers' distal ends.

13. An optical fiber adapted to sense physical variables, comprising at least two light-guiding regions A and B and so characterized that, when interrogated with light of a wavelength or wavelengths within a suitable pre-selected spectral region injected at one fiber end (the injection end) into region A, the intensity of the interrogating light propagating along the fiber is distributed between said regions A and B, the relative distribution varying as a function of the magnitude of the physical variable acting on the fiber, the fiber being adapted to automatically process said relative distribution into two resolvable optical signals the relative intensities of which are an indicator of said relative distribution and, hence, of the magnitude of the physical variable.

14. An optical fiber as claimed in claim 4 and adapted to sense forces, where said light-guiding region A is a core having an index of refraction n_1 bounded by a first cladding having an index of refraction n_2 lower than n_1, and said light-guiding region B is a second cladding around and in contact with said first cladding and having a graded index of refraction the highest value of which, n_3, is substantially higher than n_1, the fiber being so characterized that, when interrotaged with light pulses of suitably short duration injected into said core A at one fiber end (the injection end) and propagating along said core, a fraction α of the intensity of each interrogating light pulse propagating along said core is deflected from the core to said second cladding, said deflected light pulse arriving at the other fiber end (the distal end) at a time measurably different from the earlier time of arrival of the undeflected light pulse, the value of α increasing with increasing magnitude of the force.

15. An optical fiber as claimed in claim 5 and adapted to sense forces at different points along its length, the fiber being so characterized that, when interrogated with light pulses of suitably short duration injected into said core at the fiber injection end, said fraction α of the intensity of each interrogating light pulse propagating along said core at each sensing point is deflected from said core to said second cladding, said deflected light pulse arriving at the fiber distal end at a time measurably different from the earlier time of arrival of the undeflected light pulse and from the times of arrival of the light pulses deflected at other sensing points along the fiber, said times of arrival identifying the location along the fiber where the force is acting.

16. A force-sensing arrangement comprising the optical fiber claimed in claim 6 and additionally comprising:

(a) means for generating and injecting said light pulses into the fiber core at the injection end of said fiber; and

(b) photodetector means and associated electronic means for measuring the times of arrival at the fiber distal end, relative to the time of arrival of the undeflected light pulses, of the pulses of light deflected from the fiber core to said second cladding at each sensing point along the fiber.

17. An optical keyboard system consisting of a force-sensing arrangement as claimed in claim 7 and additionally comprising an arrangement of depressable keys, where said fiber is disposed under said arrangement of keys in such a manner that each key, when depressed, deflects a fraction of the intensity of the interrogating light injected into said core from said core into said second cladding simultaneously at two different points along the fiber, thus generating from each interrogating light pulse two pulses of deflected light the times of arrival of which at the fiber distal end, relative to the time of arrival of the undeflected pulse, identify the location of said key.

18. An optical keyboard system consisting of a force-sensing arrangement as claimed in claim 7 and additionally comprising an arrangement of depressable keys, where two optical fibers as claimed in claim 6 are disposed under said arrangement of keys in such a manner that the two fibers intersect under each key

of said arrangement, and where the intensity of each interrogating light pulse is distributed between the two fibers, the depression of each key causing the deflection of a fraction of the intensity of the interrogating lights propagating along the cores of each fiber at that point from said cores into said second claddings, thus generating from each interrogating light pulse two pulses of deflected light the times of arrival at the distal ends of the two fibers, relative to the time of arrival of the undeflected pulses, identify the location of each key.

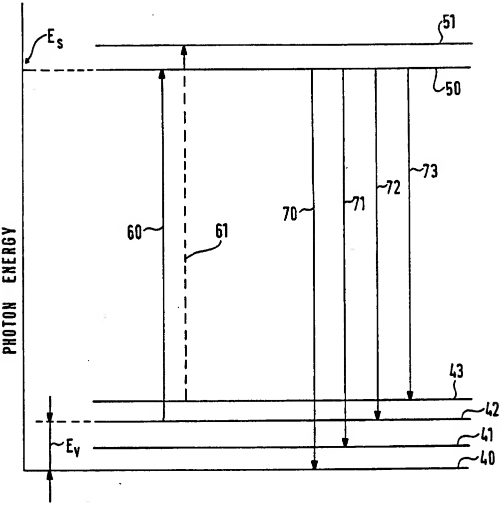


Fig. 1

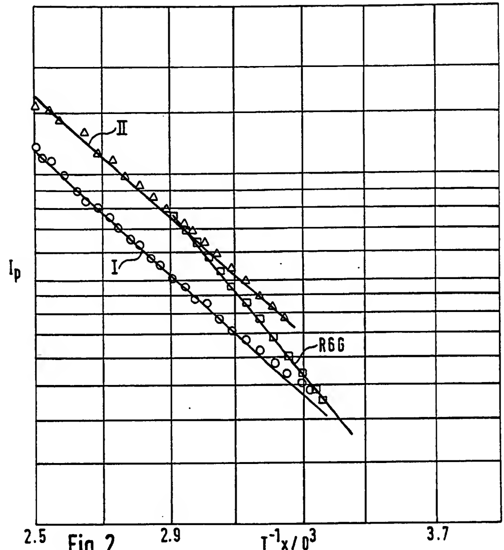

II
I
R6G
Ip
2.5
2.9
3.7
$T^{-1}x/0^3$

Fig. 2

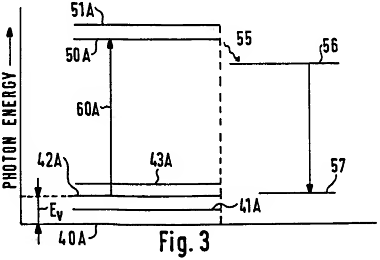

51A
50A
55
56
PHOTON ENERGY
60A
42A
43A
57
E_V
41A
40A

Fig. 3

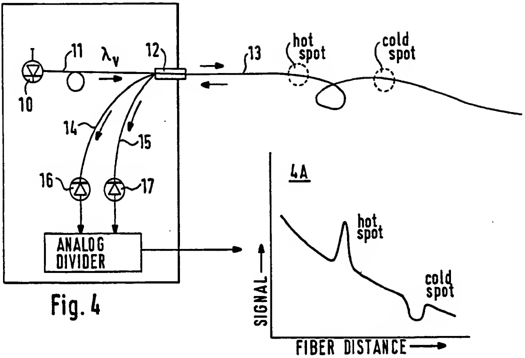

11
λv
12
13
hot spot
cold spot
10
14
15
16
17
ANALOG DIVIDER
4A
hot spot
cold spot
SIGNAL
FIBER DISTANCE

Fig. 4

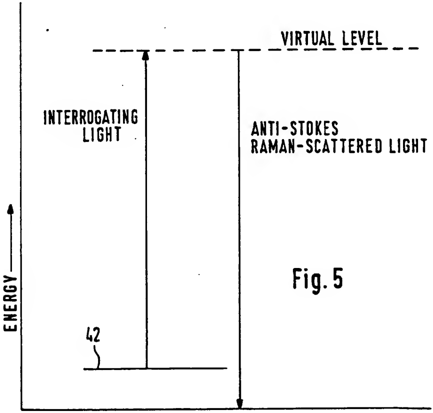

VIRTUAL LEVEL
INTERROGATING LIGHT
ANTI-STOKES RAMAN-SCATTERED LIGHT
ENERGY
42

Fig. 5

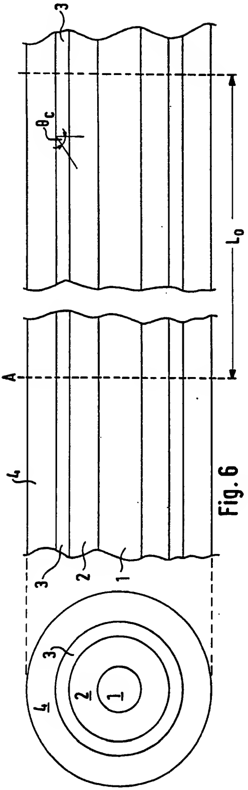


Fig. 6

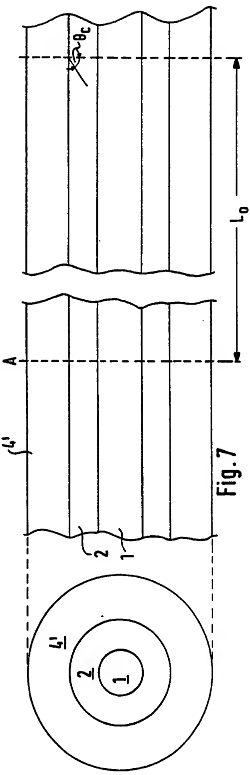


Fig. 7

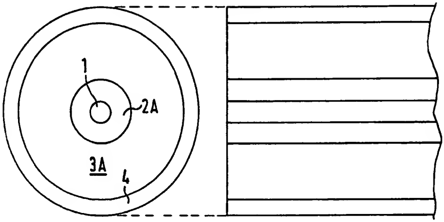


Fig.8

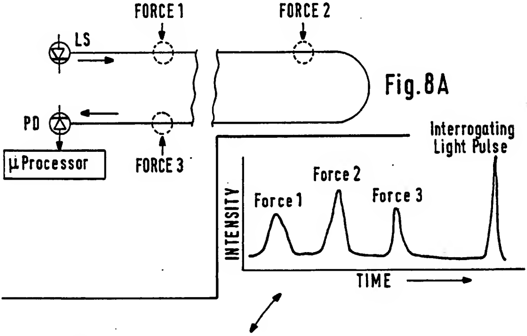


Fig.8A

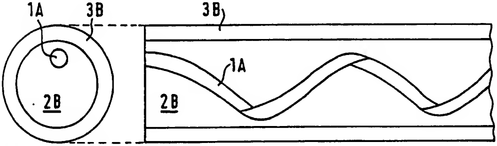


Fig.8B

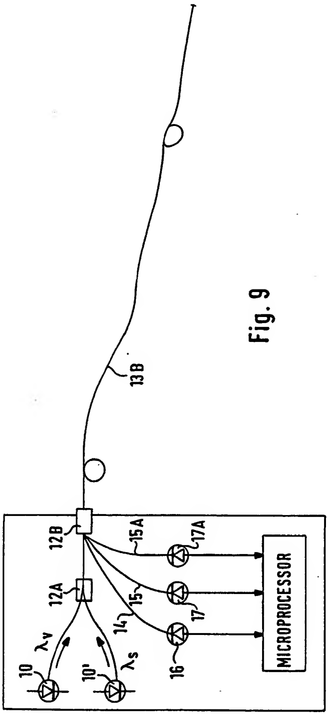

13B
12B
12A
15A
17A
15
17
14
16
10
10'
λ_v
λ_s
MICROPROCESSOR

Fig. 9

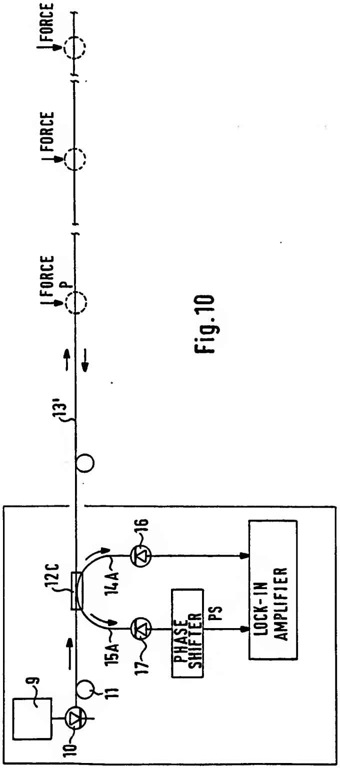

FORCE
FORCE
FORCE
P
13'
12C
14A
15A
16
17
9
10
11
PHASE SHIFTER
PS
LOCK-IN AMPLIFIER

Fig.10

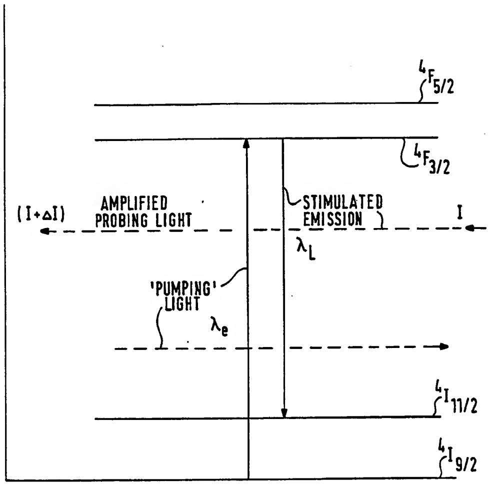

$^4F_{5/2}$
$^4F_{3/2}$
(I+ΔI)
AMPLIFIED
PROBING LIGHT
STIMULATED
EMISSION
I
λ_L
'PUMPING'
LIGHT
λ_e
$^4I_{11/2}$
$^4I_{9/2}$

Fig. 11

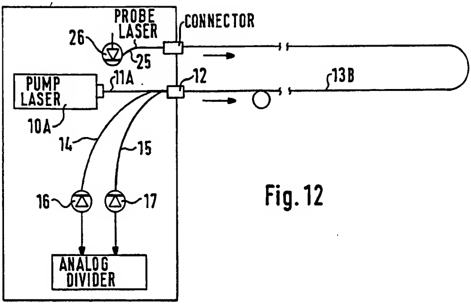

PROBE LASER
CONNECTOR
26
25
PUMP LASER
11A
12
13B
10A
14
15
16
17
ANALOG DIVIDER

Fig. 12

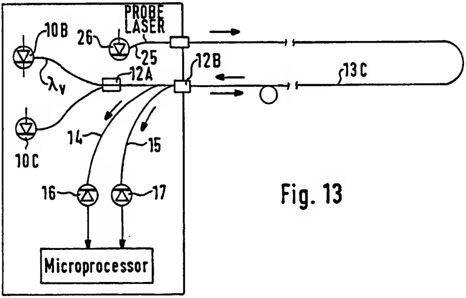

PROBE LASER
10B
26
25
12B
12A
λ_v
13C
14
15
10C
16
17
Microprocessor

Fig. 13

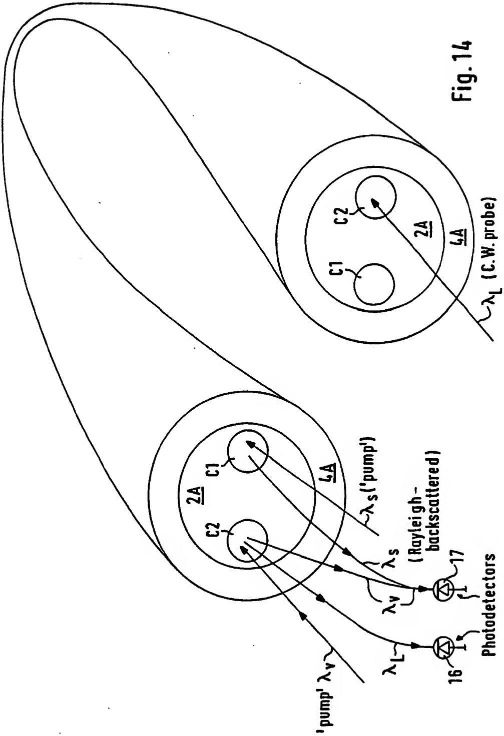

C1
C2
2A
4A
λL (C.W. probe)
C2
C1
2A
4A
λs ('pump')
λs
(Rayleigh-
backscattered)
17
λv
'pump' λv
λL
16
Photodetectors

Fig. 14

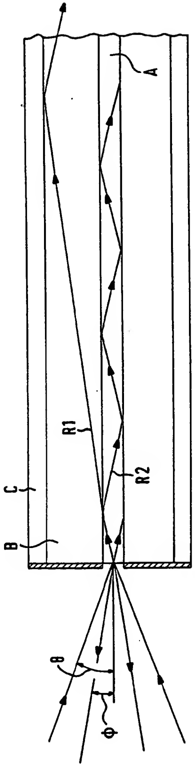


Fig. 15

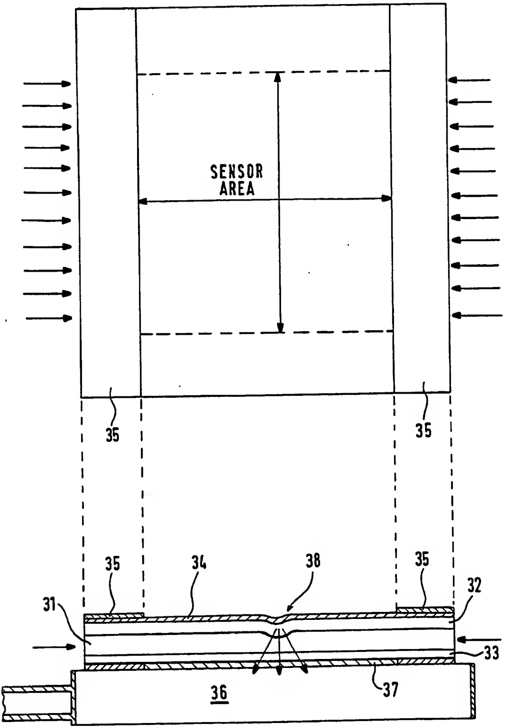


Fig. 16

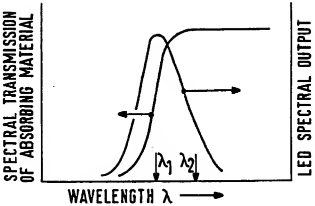


Fig.17

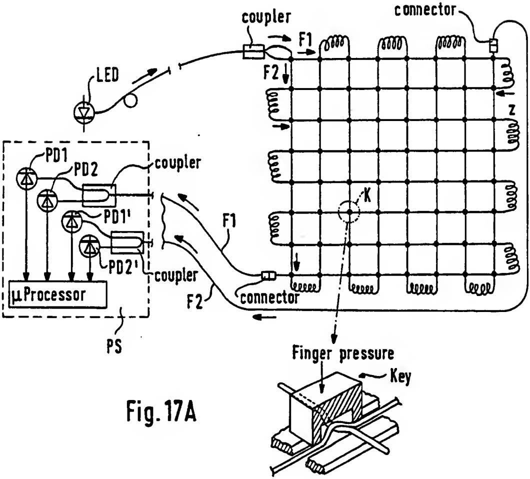


Fig.17A

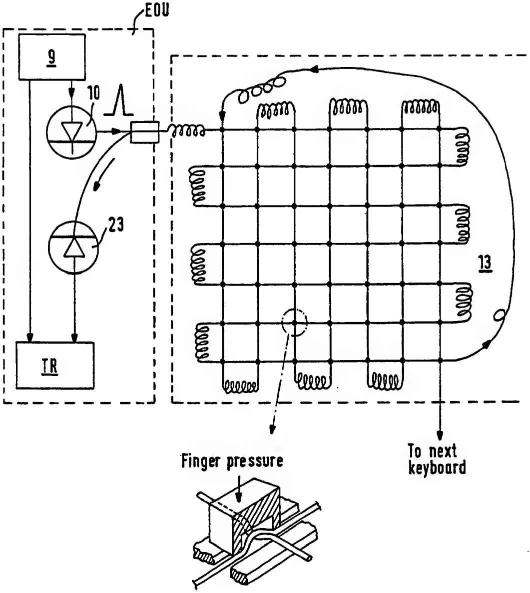


Fig.17B

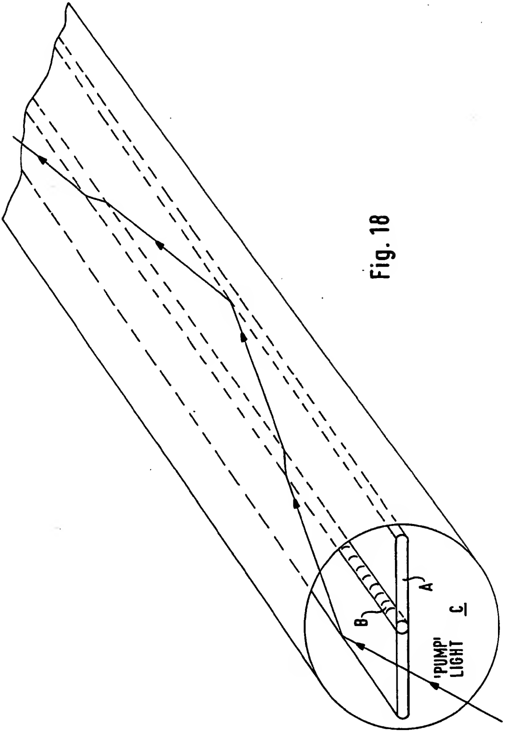
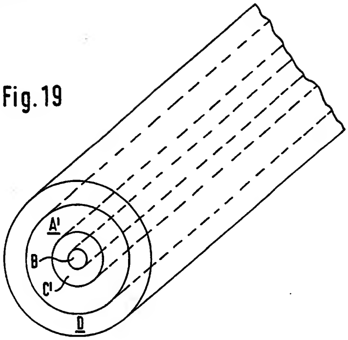


Fig. 18

Fig. 19



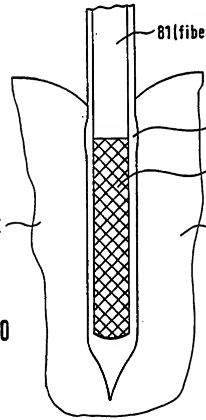


Fig. 20

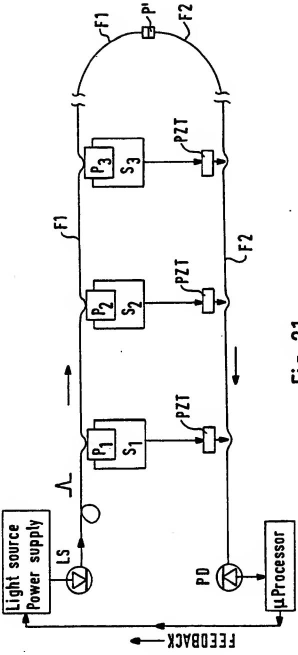

F1
P'
F2
PZT
P3
S3
F1
F2
PZT
P2
S2
PZT
P1
S1
Light source
Power supply
LS
PD
μProcessor
FEEDBACK

Fig. 21